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**IMPACTS OF WOODY DEBRIS ON FLUVIAL
PROCESSES AND CHANNEL MORPHOLOGY
IN STABLE AND UNSTABLE STREAMS**

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(i) SUMMARY

The report documents studies of degrading, unstable channels in northern Mississippi to assess whether the input of Large Woody Debris (LWD) and formation of debris jams significantly affects the evolution of channel morphology and to apply improved understanding of the role of LWD in affecting fluvial hydraulics to development of a debris management program. An examination is also made of the causes, mechanisms and locations of LWD input to the channel network, locations of storage, and debris output from headwater streams to larger channels. An understanding of these processes will help to locate potential floating debris source areas and this is vital for efficient debris management at run-of-the-river structures.

US Army Corps of Engineers Demonstration Control data-sets have been used to locate significant debris-jams with respect to planform and long-profile survey data for 23 river reaches. The reaches surveyed are between 4000 and 12000 feet long and range in upstream basin area from 3.5 to 150 square miles. They fall into several categories including stable/unstable reaches, straight/meandering reaches and reaches which have either a predominantly agricultural or a wooded riparian corridor. Debris jams in each reach have been surveyed in detail to monitor their stability and changes in associated scour/sedimentation patterns around them.

An up to date US literature review has also been compiled, covering the geomorphic significance of LWD, its hydraulic effects, impacts at structures and current LWD management strategies.

Analysis of the results indicates that localised bed scour around debris-jams predominates where the sediment load is mainly sand or silt, while there is more backwater and bar sedimentation around jams in reaches that have a gravel component to the sediment load. The number of debris jams per unit channel length decrease when moving from small to large channels, and this relationship is shown to be statistically significant using logarithmic regression analysis. The number

of LWD jams is found to be greater in actively degrading channels but is also high in actively meandering channels where bank erosion rates are similarly rapid. Stable and straight reaches have much lower debris input rates. Thalweg plots indicate that the bed topography is more varied where there is a high in-channel debris load than in reaches where debris is absent. Hence, debris jams add to the habitat diversity in addition to their morphological impacts.

The relationships between LWD formations and channel processes have been incorporated into a Drainage Basin Debris Management computer program. Input data take the form of those variables found to be significant in terms of debris-channel interactions including channel width functions, average tree height/species parameters, sediment type and channel stability. The output data given is based upon the relationships found in the current research and consists of recommendations, with explanatory notes, for debris removal, retention, relocation or input depending on the type of management strategy desired in a particular catchment or channel reach.

The long-term aim of the research is an improved understanding of the basin-wide impact of LWD dynamics in unstable and stable channel environments and the development of coherent basin-wide debris management strategies for erosion control, habitat enhancement, and maintenance/design procedure for DEC and run-of-the-river structures, based upon sound geomorphic and engineering analysis.

(ii) UNITS OF MEASUREMENT

Because field-work for this study was carried out in the U.S.A. for a Federal Agency all measurements are in Imperial Units (feet/miles). A table of conversoin factors is given below :

Conversion Factors

| From | To | Multiply By |
|---------------------------------|--------------------------------------|-------------|
| Inches (in) | Millimetres (mm) | 25.4 |
| Feet | Metres (m) | 0.305 |
| Yards (yd) | Metres (m) | 0.914 |
| Miles (Mi) | Kilometres (km) | 1.61 |
| Square Miles (Mi ²) | Square Kilometres (km ²) | 2.59 |

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1 INTRODUCTION

This research project is being funded out of the following work unit:

PROGRAM : 331 - Flood Control Structures

WORK UNIT # 32873

PRIORITY 4

WORK UNIT TITLE : Debris Control at Hydraulic Structures

PERFORMING LAB WES

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PROBLEM

During floods, debris build-up at hydraulic structures spanning streams can be a serious problem. While the problems of floating debris in reservoirs have been more or less solved, debris which piles against run-of-the-river structures with no intervening pool to catch and slow down the load causes serious operational problems and is occasionally a threat to structural integrity.

OBJECTIVE

Develop methods of handling floating debris loads in streams which eliminate threats to the operational and structural integrity of in-stream hydraulic structures.

DESCRIPTION

Quantify and classify problems Districts have had with floating debris. Examine literature for any previous mention of problems and solutions. Develop methods of alleviating most frequently caused problems. Use physical model studies, if necessary. Methods for minimizing debris problems at bridges are included as a product of this work.

BENEFIT

Reduce costs of managing floating debris at run-of-the-river hydraulic structures.

The research so far has addressed debris management at bridges and erosion control structures in the DEC monitoring watersheds. Studies in the coming year will be carried out to examine the impact of in-channel woody debris at other run-of-the-river structures such as locks, dams and weirs. This report does, however, examine the causes, mechanisms and location of woody debris input to the channel network, locations of storage, and debris output from headwater streams to larger channels. An understanding of these processes will help to locate potential debris source areas and this is vital for efficient debris management at run-of-the-river structures if debris input to the channel network is to be located and dealt with at-source rather than simply relying on remedial action at the structures themselves.

Numerous papers have been written on the subject of Large Woody Debris (LWD), concerning input processes, spacial location within the channel network, and impact upon channel morphology, flow and sediment routing.

Most studies have been undertaken in isolated reaches, although one or two, most notably Gregory, Davis and Tooth (1993), have dealt with basin-wide processes. The majority of studies, however, have been in stable gravel-bed rivers especially in headwater reaches.

Management issues have been addressed, but mainly in stable channel environments where channel processes are relatively slow.

This study aims to assess the catchment wide impact of jams over a range of channel sizes but in unstable, rapidly evolving rivers with sand, clay and loess bed and banks which are adjusting to recent human intervention through channelization, dredging and changes in farming practice.

Management strategies have been developed, based upon the observed interactions between LWD and channel processes, and the impact of debris at hydraulic structures (bridges, grade controls, bendway weirs). This research can be justified as valid because there is an insufficient understanding of basin-wide LWD processes as the scale of jam-channel interactions is likely to vary with drainage basin area, channel stability, riparian land, and channel alteration

by man. This study also examines a very different type of channel environment to that which has been predominantly studied before, that being unstable degrading channels. Another point of interest in terms of original research is that although channel degradation through knickpoint migration has been characterised by "channel evolution models" (see Schumm, 1973 and Simon, 1989) these neglect to incorporate the possible impacts of a large LWD input pulse downstream of a knickpoint, due to channel widening. LWD represents by far the coarsest elements of the "sediment load" in these channels so it is likely that debris jams will play a significant role in the channel evolution process as knickpoints migrate through reaches with large woody riparian vegetation.

This report contains an up to date literature review covering the geomorphic significance of LWD, its hydraulic effects, impacts at structures and current management strategies, as well as primary data analysis. A five week field study, in northern Mississippi, involving channel thalweg surveys and geomorphic mapping of major debris jams, in conjunction with the US Army Corps of Engineers Demonstration Erosion Control survey programme has yielded a substantial LWD data-base with planform and thalweg survey plots. These will be updated every six months with new survey data sets to build up a comprehensive picture of LWD dynamics in this channel environment.

A debris management program, written in C++, has been coded and is currently being tested using the data-sets collected. The program gives geomorphic management support information based upon the parameters and relationships developed through this research and also calculates potential scour at bridge piers due to debris build-up. The executable source code is included on a disk in this report, along with a user support manual which contains test data. This program will be modified as processes and relationships are developed further and will also be integrated with a GIS data input interface. This GIS front end is currently being developed by Peter Cheesman, a masters student at the University of Nottingham.

2 LITERATURE REVIEW

2.1 INTRODUCTION

In a literature review of published material then available, Hickin (1984) suggested that vegetation may influence channel processes through five mechanisms:

- a) Flow resistance
- b) Bank strength
- c) Bar sedimentation
- d) Formation of log jams
- e) Concave-bank bench deposits

He also stated that the literature concerning this subject was of two main types: that dealing with the indirect influence relations between vegetation, water, sediment yields and river morphology; and that dealing with the direct impact of channel vegetation on channel morphology. The latter was, in 1984, limited to only a few papers.

There has been a rapid increase in recent years, however, in the number of studies concerning Coarse Woody Debris (CWD) or Large Organic Debris (LOD) (Hogan, 1987) and its accumulation as jams or dams in river channels. This is probably a result of the current shift from hard to soft engineering practices and adoption of a more holistic approach to river basin and channel management.

Studies can be grouped by topic into those dealing primarily with :

- a) Input process
- b) In-channel effects
- c) Fluvial transport processes.

Each of these processes varies depending upon stream size relative to CWD size (Nakamura et al, 1993).

Most studies have been carried out in essentially stable channel environments in the U.S. and Canadian Pacific Northwest, in the U.K., and in New Zealand. Instability in the form of landsliding, is cited by Pearce & Watson (1981) as a means for debris to enter channels, but the impact of debris on inherently unstable channels has not been assessed.

2.2 QUANTITY AND DISTRIBUTION OF LWD

2.2.1 Input Processes

Large Organic Debris enters river systems by two main processes; either from outside the channel due to bank erosion, mass wasting, windthrow, collapse of trees due to ice loading or biological factors (death and litter fall (Keller, 1979)); or from inside the channel, through erosion and flotation of material (Hogan, 1987), (Figure 2.1). Once in a channel, debris may form into jams or dams.

In this paper the term "jam" is used for a partial blockage and "dam" refers more specifically to the complete blocking of flow along a channel.

2.2.2 Formation of Jams

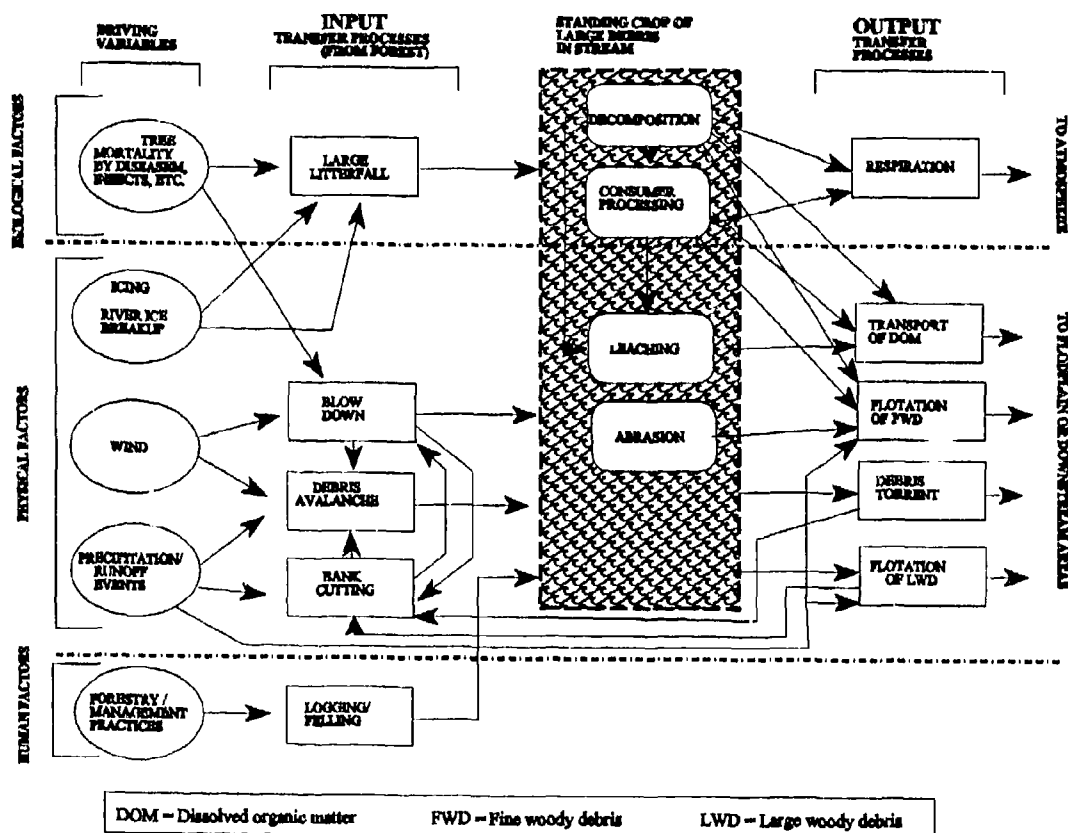
Jams often form around "key coarse woody debris" (Nakamura, 1993), which are usually large, whole trees that have entered the channel by one of the mechanisms mentioned above and which are anchored to the bed or banks at one or both ends. Smaller debris floating down the channel then accumulates against this feature, which acts as a sieve to debris and, later to sediment. If there is no fine debris present a jam may never form, so that the impact of key-debris is minimal.

2.2.3 Residence time of debris jams

The residence time, or permanence, of debris jams is an important factor, which determines the extent to which channel morphology will be adjusted. Assessing residence time is difficult and estimates range between 12 months, for a 36% change or removal (Gregory & Gurnell (1985), to 40-90 years (Hogan, 1987), to 200 years in streams in British Columbia (Keller

DYNAMICS OF WOODY DEBRIS

Figure 2.1



(adapted from Keller & Swanson, 1979)

& Tally, 1979). This factor largely depends upon the occurrence of long return period floods and is, therefore, river specific.

2.3 IN-CHANNEL GEOMORPHIC SIGNIFICANCE

2.3.1 Effects of channel scale

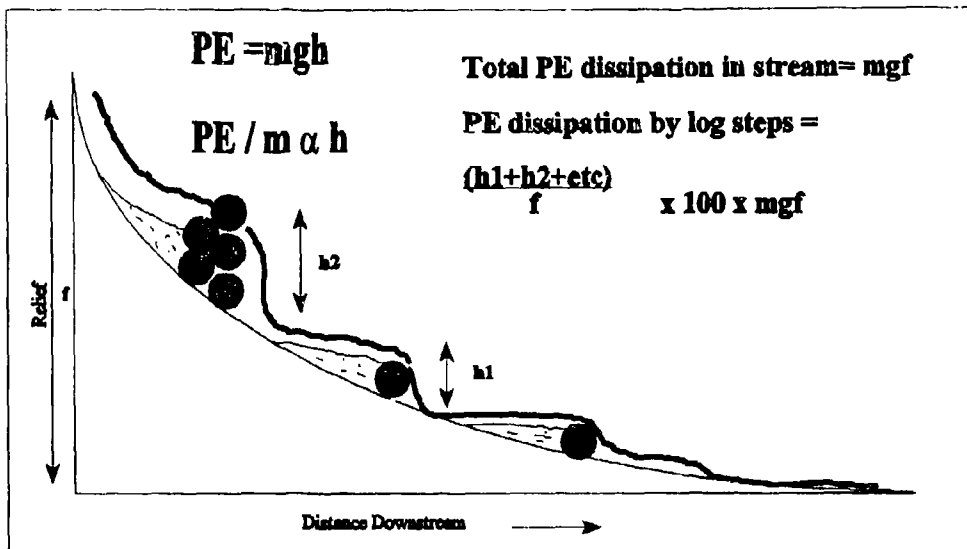
It is important to recognise that processes are scale dependent. For example, Zimmerman et al. (1967) found that debris accumulations in a very small stream completely obscured the usual hydraulic geometry relations, while Robinson & Beschta (1990), and Keller & Tally (1979) suggest that debris loadings increase with stream size. Gregory et al. (1985), have characterised jams into three types :

- 1) Active (form a complete barrier to water and sediment movement, and create a distinct step or fall in the channel profile)
- 2) Complete (a complete barrier to water/sediment movement but no step formed)
- 3) Partial (only a partial barrier to flow)

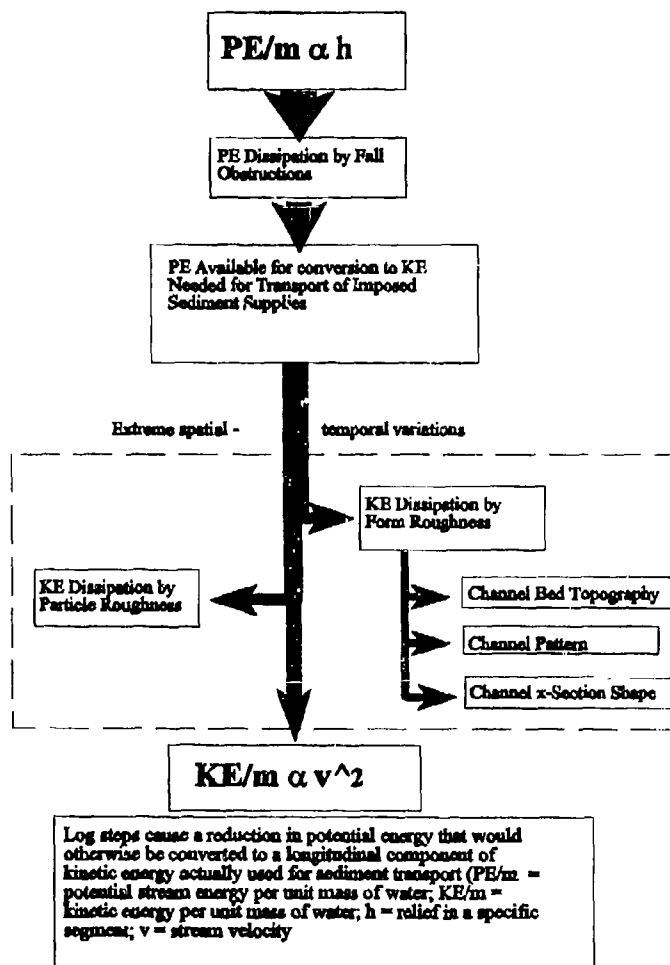
They suggest that these types become sequentially more prevalent as channel size increases. In this study, the Gregory et al. classification was incorporated into the field analysis, as it was evident that jam size and orientation were extremely important in terms of channel process control. Similarly, Robinson & Beschta's (1990), Deflector, Underflow, and Dam flow direction criteria and debris zonation criteria were used in the field studies (see Appendix D).

In small streams debris will accumulate where it falls because the flow is not competent to move material, but in larger streams distinct jams may form, while in even larger rivers debris may never accumulate because it is carried away downstream.

Once trees fall into a stream, their influence on channel form and process may be quite different to that when they were on the banks, changing from stabilizers to destabilizers through local scour and basal erosion. Thus, jams represent a type of auto-diversion: that is, a change in channel morphology triggered by the fluvial process itself. The impact on morphology is



Potential stream energy per unit mass of water (PE/m) is directly proportional to h , or the relief in a specific stream.
 PE dissipation by log steps = Cumulative change of water surface elevation ($h_1 + h_2 + \text{etc}$) as a percentage of total stream relief (f)



(adapted from Marston, 1982)

dependent primarily on the channel width/tree height ratio and on debris orientation relative to the flow. Mean discharge and the dominant discharge recurrence interval are also important because the higher the flow is relative to jam size, the smaller will be the jam's impact in terms of acting as a flow diverter and roughness element. The principle effects of debris upon channel morphology are described below.

2.3.2 Impact of debris jams upon channel morphology

Mosley (1981) found at Powerline Creek, New Zealand, that along 40% of the stream channel bed contours, the location of riffles, pools and gravel bars were related to flow patterns induced by organic debris. Studies in the Pacific Northwest have also shown that a considerable proportion of the vertical fall of channels can occur at the sites of debris jams, accounting for 60% of the total drop in some streams such as Little Lost Man Creek in Northern California (Keller & Tally, 1979). Debris jams therefore act as local base levels and sediment storage zones which provide a buffer to the sediment routing system. On this basis, Klein et al. (1987) argue that jam removal can cause upstream base level change and bank erosion. Random debris input will also distort the riffle-pool sequence making it less systematic, so that the channel in long profile has very little spatial memory, or periodicity (Robinson & Beschta, 1990).

Potential energy is dissipated at jams, with energy loss being as much as 6% of total potential energy (MacDonald et al., 1982). Stream power distribution is altered and further effects arise through the influence of jams on the location of erosional and depositional processes and through the backwater affect created by jam back-pools (Keller et al. 1976). Thus, in small, stable channels, log steps generally increase bank stability and reduce sediment transport rates by creating falls, runs and hydraulic jumps. Figure 2.2 shows how potential energy is lost through a log-step sequence. This localised dissipation of energy can, however, result in associated local scour and bank erosion which causes channel widening, although Keller & Tally (1979) also observed channel narrowing, caused by flow convergence underneath logs, with sediment storage

upstream and a scour-pool downstream.

As the channel width/tree size ratio becomes greater than unity flow is diverted laterally, inducing bank erosion and local pool scour. Hogan (1987) found that in undisturbed channels in British Columbia organic debris diagonally crossing the channel resulted in high width and depth variability, whereas in catchments where there had been logging operations, the majority of in-channel discarded timber was parallel to the flow, and subsequently became incorporated into the stream banks, protecting them from erosion. Nakamura & Swanson (1993) have suggested that there is a progression of debris/channel interactions, ranging from base level control and possible local widening in low-order streams, to lateral channel shifts and increased sinuosity in middle-order channels, to bar formation and flow bifurcation in high-order streams. This last process has been documented by Nanson (1981), again in British Columbia, who found that organic debris deposited at low flow provided the nuclei for development of scroll bars, through the local reduction of stream power. Hickin (1984) also observed crib-like bar-head features, but was undecided as to whether the debris caused bar formation, or whether the bars pre-dated and trapped the debris. In either case organic debris would, at the very least, enhance sediment deposition and bar formation.

2.4 HYDRAULIC SIGNIFICANCE OF LWD

A comprehensive investigation of the hydraulic effect of LWD in rivers has not been documented. However some studies have investigated the effect of LWD on channel roughness, the hydrograph, velocity distribution and water surface profile

2.4.1 Effect of LWD on channel roughness

The Manning's "n" equation generates a roughness coefficient from all sources in the channel. This flow equation is widely used by river engineers who select values of "n" from tables in Chow (1959) or from photographs in Barnes (1967). The range of n coefficient in normal channels is from 0.025 to 0.15. For heavily congested streams less than 30m wide n ranges from 0.075 to 0.15. Irregular and rough reaches of large streams have values of n from 0.035 to 0.10.

$$n = \frac{R^{2/3} S^{1/2}}{V} \quad \text{or} \quad n = \frac{1.49}{V} R^{2/3} S^{1/2} \quad (1.1)$$

R = hydraulic radius (m), S = energy slope, V = mean velocity (ms^{-1}), 1.49 = conversion to fps units.

The hydraulic effect of LWD varies as a function of relative depth of flow. Bevan et al. (1979) found that when LWD is high in relation to flow depth the roughness coefficient is extremely high (Manning's $n > 1$). As LWD becomes structurally submerged it exerts less influence on flow hydraulics. Shields and Smith (1992) measured a large decrease in Darcy-Weisbach friction factor as discharge increased, and also observed that friction factor, for cleared and uncleared reaches, converged at high flows. Indirect evidence for these findings is provided by investigations of downstream hydraulic geometry which shows that roughness generally decreases as channel size increases (Wolman, 1955). Petryk and Bosmajian (1975) derived an equation to predict Manning's

n as a function of density of vegetation in the channel, hydraulic radius, Manning's n due to boundary roughness and a vegetation drag coefficient.

$$n = n_b \sqrt{1 + \frac{Cd \sum A_i \left(\frac{1.49}{n_b} \right)^2 \left(\frac{A}{P} \right)^{2/3}}{2gAl}} \quad (1.2)$$

n_b = Manning's boundary roughness coefficient excluding the effect of vegetation; Cd = drag coefficient for vegetation (assumed to be 1); A_i = projected area of the i th plant in the streamwise direction; A = cross-sectional area of flow; L = length of the channel reach being considered; P = wetted perimeter of channel.

In this formula the expression $Cd \sum A_i / AL$ represents the density of vegetation in the channel.

Gippel et. al. (1992) note that a problem with this formula is selecting a value for the drag coefficient Cd . Petryk and Bosmajian assumed a value of 1 but this applies to cylinders in infinite flow. In streams, interference from nearby obstructions and the effect of blockage on the drag coefficient need to be considered.

The Manning equation is however, inappropriate in situations where there is a high degree of obstruction in the channel, particularly where $n > 1$. The Manning equation was developed empirically to describe open channel situations with fully turbulent flow where friction is controlled by drag from the channels surface. The equation attaches significance to the hydraulic radius which may be irrelevant if the channel is heavily choked with LWD.

Smith and Shields (1992) studied the effects of varying levels of LWD density on the physical aquatic habitat of South Fork Obion River, Tennessee, USA. Two secondary objectives in this study were to develop and demonstrate a method for quantifying LWD in a given reach and to relate the quantity of LWD to reach hydraulics. An approach similar to that used by Petryk and Bosmajian (1975) was used to calculate the effect of LWD on channel roughness. The LWD density in a reach was calculated using the following formula :

$$DA = \sum_{i=1}^n \frac{A_i}{A} L_r = (1 / L_r) \sum_{j=A}^D F_{bj} \sum_{k=1}^3 N_{j,k} F_{wk} \quad (1.3)$$

where

n = total number of LWD formations in the reach

A_i = area of the i th debris formation in the plane perpendicular to flow

A = reach mean flow cross-sectional area

L_r = reach length

F_{bj} = formation type weighting factor for j th formation type.

$N_{j,k}$ = number of type j LWD formations in K th width category.

F_{wk} = weighting factor based on LWD formation width category.

See Appendix B for a description of the weighting factors.

Rather than Using Manning's n , the more theoretically based Darcy-Weisbach flow resistance equation was used, which can be expressed as:

$$f = \frac{8gRS_w}{V^2} \quad (1.4)$$

where

f = Darcy-Weisbach friction factor; R = hydraulic radius; S_w = water surface slope

In a channel reach where LWD plays a major role in flow resistance, total resistance can be expressed as:

$$f_t = f_b + f_d \quad (1.5)$$

where

f_t = total Darcy-Weisbach friction factor

f_b = boundary friction factor excluding LWD effects

f_d = friction factor due to LWD

Total head loss is the sum of a boundary friction loss and a LWD blockage loss, as follows:

$$h_L = S_E L = \frac{[(f_b L / 4R) + K_d] V^2}{2g} \quad (1.6)$$

where

h_L = total head loss

S_E = slope of the energy gradient

K_d = dimensionless loss coefficient (dependent upon LWD density)

The energy slope can be calculated using a total friction factor from the Darcy-Weisbach equation:

$$S_E = \frac{f_t V^2}{(8gR)} \quad (1.7)$$

Substituting this expression for S_E into equation 6 gives:

$$f_t = f_b + \frac{4RK_d}{L} \quad (1.8)$$

Therefore:

$$f_d = \frac{4RK_d}{L} \quad (1.9)$$

The ratio K_d/L may be expressed in terms of the LWD density as:

$$K_d / L = DA \quad (1.10)$$

Smith and Shields calculated values for f_b using curves developed by Alam and Kennedy (1969) and hydraulic parameters determined from dye tracer tests in the LWD reaches, which provide direct discharge and velocity estimates (Richards 1982), and the median bed grain size determined from sieve analysis. Values for f_d were then calculated using equations 1.3, 1.9 and 1.10. They then compared computed values of f_t with values measured using dye test.

The results of their study showed a reasonable positive correlation between the measured and computed friction factors. However, they recognise that considerable refinement and site-

specific adaptation may be in order, and that the method does not account for local energy loss because of bends or flow expansion and contraction at bridges, debris dams, or riffles. The method does have a sound theoretical basis however and could be usefully employed in future research into LWD hydraulics.

2.4.2 Effect of LWD on velocity distribution

LWD clearly influences the direction and magnitude of flows currents within stream flow, but few data have been documented in the literature. Swanson (1979) produced detailed maps of debris jams indicating flow with directional arrows. Smith and Shields (1990) reported that the removal of LWD from a river 18-23m wide 3.5 to 4.5 m deep produced more uniform flow, and less of the channel was occupied by eddies or regions of reduced velocity.

2.4.3 Effect of LWD on stage/discharge relationships, the hydrograph and flood frequency

LWD is often removed because it is assumed that this will achieve a significant reduction in channel roughness which will allow a higher mean flow velocity and thereby increase channel capacity. There is some evidence to support this assumption. For example Smith and Shields (1990) measured the mean flow velocity in two cleared reaches of a river to be 0.04 m/s and 0.34 m/s. In an uncleared reach of the same river the mean velocity was 0.27 m/s. MacDonald and Keller (1987) also found that there was a local increase in velocity by up to 250% as a result of LWD removal and a decreased sinuosity of the low flow thalweg. According to Gippel et al. (1992) the Murray-Darling Basin Commission calculated a theoretical reduction in water level of 0.3 - 0.4 m after the removal of approximately 200 snags per kilometre. However, later analysis of flow records indicated a reduction of only 0.2 m. In theory there should be a statistical reduction in the magnitude and frequency of overbank flooding where debris is removed from a channel because of the increased channel capacity. Bodron (1994), used a dynamic routing model to demonstrate

changes in both stage and duration of flood events before and after LWD removal, using Manning n values calculated in the study by Smith and Shields at South Fork Obion River, west Tennessee. Despite the increase in channel cross-sectional area due to LWD removal being ignored, small reductions in flood height and duration were calculated based solely on the change in Manning's n values. Bodron also notes that flood stage would be reduced further if sediment accumulations at each jam site had been removed. However, according to Gippel et al (1992) many claims that this effect has been achieved lack any supportive evidence. Counterclaims also lack supportive evidence, because of the difficulty of isolating the hydraulic effect of LWD removal. It is even possible that LWD removal might increase flood peaks, because the downstream flood wave is not attenuated so much.

Gregory et. al. (1985) found that LWD ponds water which results in an increase in water depth and a decrease in velocity, which, at low flows influences travel time significantly. At high flows, however, the ponding effect of LWD is drowned out.

Shields and Nunnally (1984) noted that because large accumulations of LWD have a damming effect on the flow which locally elevates the base level they can be treated as geometric elements within the channel, rather than simply as roughness elements, in backwater profile computations.

2.4.4 Modelling the hydraulic effect of LWD

Most studies of resistance to flow in rivers have concentrated on small-scale roughness, especially skin friction offered by bed sediments, where the size of the roughness element is small compared to the flow depth. LWD on the other hand represents large-scale roughness, for which skin friction is small compared with form drag (Petryk and Bosmajian, 1975). Flow conditions associated with the presence of LWD in streams varies from sub-critical to super-critical depending on the dimensions of the LWD and the depth of water.

Gippel et. al. (1992) used the momentum principle to determine the hydraulic effect of LWD, the effect being quantified in terms of afflux or backwater effect. If flow is subcritical (Froude number < 1), apart from local disturbance of the velocity profile, LWD only has an influence in the upstream direction. There are often practical difficulties with directly measuring the afflux at debris jams, however, an alternative to direct measurement is prediction on the basis of a known relationship between afflux and more easily measured parameters. Gippel et. al. used the results of a laboratory hydraulic study to develop a method of determining the afflux caused by LWD. See Figure 2.3

They propose the use of the following equation to calculate afflux :

$$\Delta h = \frac{h_3 \left[(F^2 - 1) + \sqrt{(F^2 - 1)^2 + 3C_D B F^2} \right]}{3} \quad (1.11)$$

where

$$\Delta h = \text{afflux} = h_1 - h_3 \text{ (m)}$$

and the drag coefficient :

$$C_D = \frac{F_D}{\frac{1}{2} \rho U_1^2 L_w d} \quad (1.12)$$

F_D = drag force (N)

ρ = density of water (approx. 1000 kg/m³)

U_1 = mean velocity at section upstream of object (m/s)

L_w = projected length of LWD in flow (m)

d = diameter of LWD (m)

and the Froude number:

$$F = \frac{U_3}{\sqrt{g h_3}} \quad (1.13)$$

U_3 = mean velocity at section downstream of object (m/s)

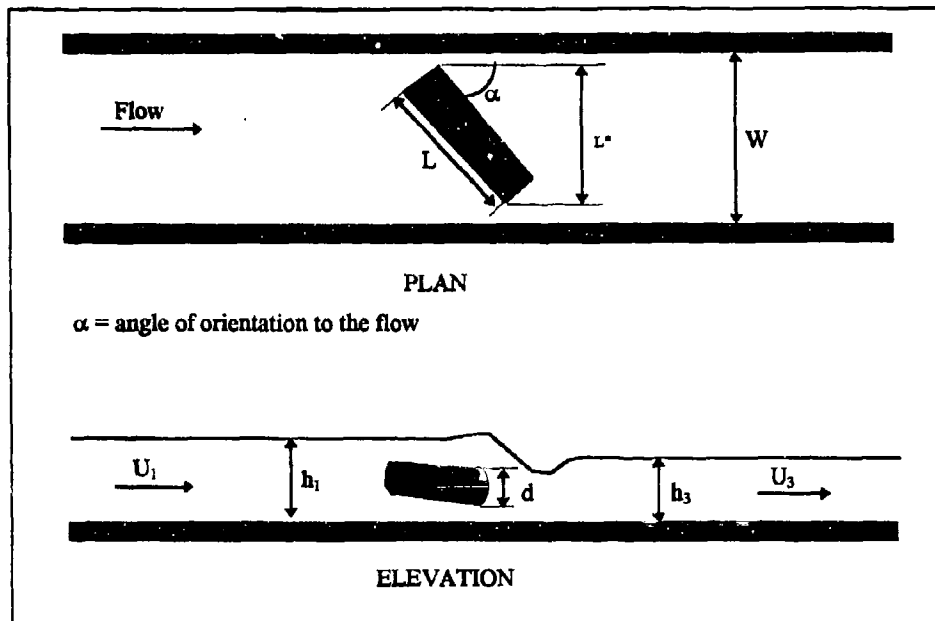
h_3 = water depth downstream of LWD (m)

and the blockage ratio:

$$B = L \cdot d / A \quad (1.14)$$

$A = W \cdot h_1$ = cross sectional area of flow (m^2)

Figure 2.3 Definition sketch of LWD model used in flume by Gippel et. al. (1992)



Thus the afflux depends on F , C_D and B . The Froude number can be calculated from direct measurement or from flow records. B can be found from survey. The problem comes in selecting an appropriate drag coefficient. The drag characteristics of a cylinder in infinite flow are well known (Petryk and Bosmajian, 1975). Less is known about drag on cylinders within boundaries (the "blockage effect") where the drag coefficient is increased. Gippel et al. conducted experiments on LWD models to determine drag force, using a towing carriage and water tunnel. Froude number, LWD length to diameter ratio and LWD depth from the bed all affected drag coefficient, but were much less important than the blockage effect, angle of orientation to the flow and the shielding effect (of one piece of LWD behind another). A suitable drag coefficient (C'_D) for the

LWD in question can therefore be selected from their experimental results (Gippel et. al. 1992, figures 3.8 or 3.12) on the basis of its overall shape and angle of orientation. See Appendix C. The drag coefficient should then be adjusted for the blockage effect, which can be calculated using the following equation developed by Gippel et. al. using their empirical data from flume studies :

$$C_D = C'_D (1-B)^3 \quad (1.15)$$

where

C'_D = drag coefficient in infinite flow.

These data are then substituted into equation 1.11 to calculate the afflux.

Predicted and measured afflux values resulting from the flume study were very closely correlated, and they conclude that the flume conditions did not seriously violate any of the assumptions in equation 1.11.

The proposed method of afflux estimation was then applied to data collected from the Thomson River, Victoria, and revealed that de-snagging there would produce a reduction in stage of only 0.01m at bankfull flow.

In conclusion then, this method of backwater, or afflux calculation due to individual items of LWD could be used as a tool to help determine whether the afflux reduction due to LWD removal would have a positive impact according to the perceived management requirements or whether it could be left in place perhaps, re-orientated, lopped or even re-introduced where sympathetic rehabilitation management is desirable.

Appendix C contains a summary of the method developed by Gippel et. al. (1992) for predicting the afflux generated by LWD.

Young (1991) carried out a series of experiments in a flume using scaled LWD pieces in order to determine the order of magnitude of the increase in flood levels caused by LWD at different positions within the channel cross-section. Results indicated that the frontal area of LWD, as a percentage of the channel cross-section, had to be very high in order to cause a significant rise

in stage (a 10% stage rise required a frontal area of 0.8 x the channel cross-section). LWD position variables were also examined. For example, it was found that LWD near the bed will cause a greater hydraulic effect than LWD higher in the cross-section, and that a 50 % reduction in the stage rise (from that due to LWD aligned perpendicular to the channel) requires a 40 degree rotation of the LWD from the perpendicular. Young concludes that his results indicate that the amounts of LWD which are found in lowland rivers, in Australia, will seldom have a significant effect on flood levels, except where large log-jams form. However, he also notes that where rivers are used to supply irrigation water tolerances in water level are often lower and hence LWD removal may be necessary more frequently.

Cherry and Beschta (1986) conducted a series of tests using a 6 metre trapezoidal flume, with sand bed and wooden dowel LWD pieces to evaluate the effect of debris on local channel morphology in terms of depth and area of associated scouring. Maximum scour depths were significantly correlated with both the vertical orientation of the dowel (Beta angle) and the channel opening ratio (ratio of projected dowel length to channel width). Scour surface area were significantly correlated with both flow depth and vertical orientation. Results indicated that scour depths were maximum when LWD was flat on the bed, and then declined as the Beta angle increased. Scour depths were also at a maximum when the horizontal angle (alpha angle) of the debris to the channel was 90 degrees (perpendicular to the flow), with the second greatest depths occurring when the debris was angled up-stream at 150 degrees. Similarly, as the Beta angle was increased so the area of scouring declined and the area of scour was at a maximum when the debris was orientated at 90 degrees to the channel. It was found that as flow depth increased, so the area of scour increased. Finally, it was observed that upstream-orientated dowels deflected flows towards the bank, while downstream orientated dowels deflected flow away from the bank and therefore appear to provide better protection from scour related failure.

2.5 IMPACT OF LWD AT BRIDGES

2.5.1 Theory

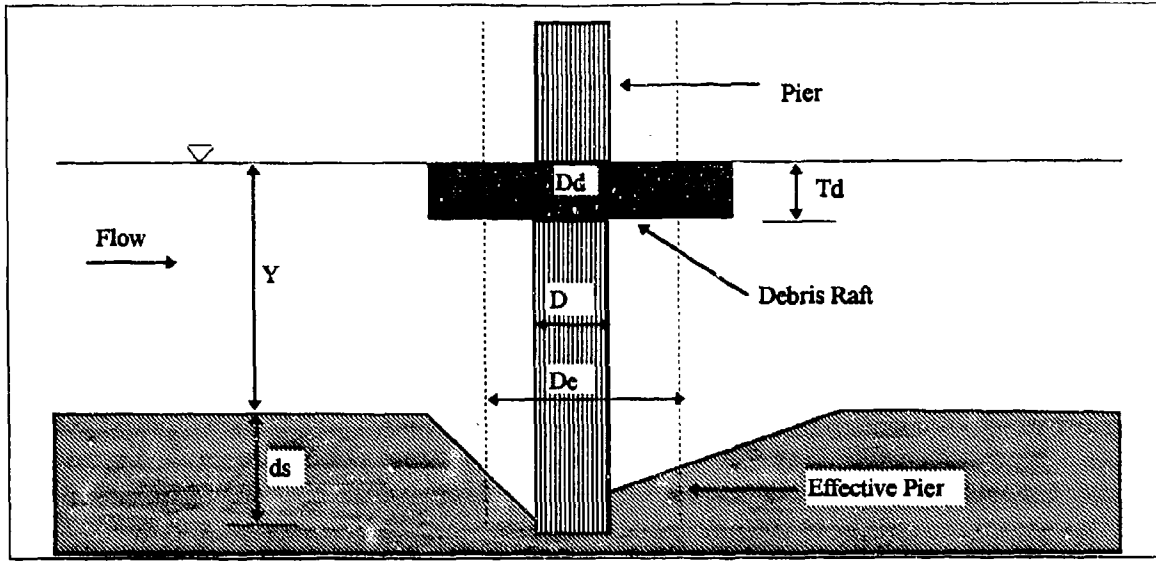
There are only a limited number of studies that have addressed the problem of debris accumulations at bridges. Melville & Dongol (1992) look at the problem of pier scour due to debris, while Simons & Li (1979) have used a probabilistic approach to quantify the rate of bridge span blockage by debris and the subsequent backwater effect and pressure forces generated on the piers.

Local scour at bridge piers has been extensively investigated. However the impact of debris rafts at piers which create additional flow obstruction and therefore increase scour depths has been largely neglected. A design method for estimation of scour depths at piers is presented by Melville and Sutherland (1988), based on envelope curves from laboratory data. The largest local scour depth at a cylindrical pier is estimated to be $2.4D$ where D is the pier diameter. $2.4D$ is reduced however using multiplying factors where clear-water scour conditions exist, the flow is relatively shallow, and the sediment size relatively coarse. In the case of non-cylindrical piers, additional multiplying factors to account for piers shape and alignment are applied. Consideration of the likelihood and extent of floating debris is not addressed by Melville and Dongol (1992) but is assessed by Simons and Li (1979). Melville and Dongol do note however that single cylindrical piers are the least likely to accumulate debris, and that the free space between columns is seldom great enough to pass debris. Prediction of the size of possible debris rafts remains the biggest problem.

The experimental arrangement used by Melville and Dongol is shown in Figure

2.4.

Figure 2.4 Experimental Setup



The design curve for pier scour without debris accumulations, developed by Melville and Sutherland (1988) is described by the following two equations:

$$\frac{ds}{D} = 1.872 \left(\frac{Y}{D} \right)^{0.255} \quad \left(\frac{Y}{D} < 2.6 \right) \quad (1.16a)$$

$$\frac{ds}{D} = 2.4 \quad \left(\frac{Y}{D} \geq 2.6 \right) \quad (1.16b)$$

This shows that scour depth increases with increasing flow depth towards a limiting value for $Y/D > 2.6$. The same trend is found for piers with debris accumulations for values of $Y/D < 4$. At higher values of Y/D scour depths decrease again because the proportion of pier length covered by debris decreases. For deep flows the effect of debris would become insignificant and tend towards the value $ds/D = 2.4$.

The effective diameter of a pier with a debris accumulation, D_e , is given by,

$$D_e = \frac{T_d^* D_d + (Y - T_d^*) D}{Y} \quad (1.17)$$

According to (1.17) D_e is calculated as a weighted average of an effective length $T_d^* = 0.52 T_d$ of the debris raft with diameter D_d and a length of the pier $(Y - T_d^*)$ with

diameter D . See figure 2.4. (The factor 0.52 was determined by evaluating the limits of T_d and D_d/D for the hypothetical case where D is assumed to be zero and the debris is assumed to extend to the base of the scour hole).

D can therefore be substituted for D_e to calculate scour depth at piers with debris accumulations using the Melville and Sutherland design method. Conversely a maximum allowable T_d and D_d can be calculated by specifying an upper scour depth within an acceptable factor of safety for a given pier size.

The rate of debris accumulation at bridge is difficult to quantify. The only method found in the literature is that presented by Simons & Li (1979) in an Msc thesis by Callander entitled "Fluvial Processes occurring at bridge sites" (from CSU, 1980).

According to Simons & Li, the trapping efficiency of a bridge is determined by:

- 1) Clearance beneath the bridge
- 2) Span lengths
- 3) Size and concentration of debris elements

The following possible consequences are identified which can result from debris blockage:

- 1) Backwater effects
- 2) Potential local flow diversion
- 3) Channel avulsion
- 4) Bridge failure

Simons & Li express the volume of debris as a fraction of the sediment yield, and state a vegetation debris yield of 1%. In an attempt to estimate the number and volume of trees arriving at a bridge they utilise the volume of flood-plain erosion necessary to yield a tree, and use a representative tree size for the watershed.

Trees are assumed to be cylindrical with a diameter D_t , and a height H_t . The span between piers is L_s and the clearance between the water surface and the underside of the bridge is C . The chance that a tree will be trapped depends on a larger diameter however, D_b , which represents either the canopy dimension or the root zone, whichever is larger. See figure 2.5.

If $H_t > L_s$ the probability of at least one average tree being trapped is 100%. The blocked area is then estimated to be, NH_tD_t , where N is the equivalent number of average trees assumed to be trapped against the upstream face of the bridge.

If $H_t < L_s$ a probabilistic approach is used.

P_t is the probability of a tree being trapped, and as the blockage beneath a span increases so the chance of other trees being trapped increases. The probability of the first tree being trapped is assumed to be a ratio of half the tree diameter, D_b , to the total waterway area beneath a span, L_sC .

$$PT_1 = \frac{\frac{1}{2}(\pi D_b^2 / 4)}{L_s C} = \frac{\pi D_b^2}{8 L_s C} \quad (1.18)$$

Li (1980) observed that a tree caught on a pier will in general lie with its trunk in the direction of flow. A tree thus trapped offers an area of

$$\frac{1}{2}(\pi D_b^2 / 4) = \pi / 8 D_b^2 \quad (1.19)$$

to trap other debris.

In general when $(m-1)$ trees are trapped beneath a span the probability of an m th tree becoming trapped is

$$PT_m = \frac{\pi D_b^2 / 8}{L_s C - (m-1)(\pi D_b^2 / 8)} \quad (1.20)$$

The probability of passing all NT trees from the watershed is

$$(1-PT_1)^{NT} \quad (1.21)$$

The probability of passing all NT trees from the watershed is

$$(1-PT1)^{NT} \quad (1.21)$$

The probability of at least one tree being trapped at a span is

$$P1 = 1-(1-PT1)^N \quad (1.22)$$

where N is the equivalent number of average trees arriving at the span. According to Li (1980) most trees will stay close to the bank, thus

$$N = NT / 2 \quad (1.23)$$

The probability that m trees will be trapped is

$$Pm = [1-(1-PTm)^{N-(m-1)}]P(m-1) \quad (1.24)$$

On this basis the probability of a least m trees being trapped (for any $m < N$) can be estimated. The value of m can correspond to a chosen design criteria, for example maximum values of Td and Dd in the Melville and Dongol method. In order to calculate Td and Dd there needs to be an estimate of the blockage area. It is assumed that debris elements stack up and that trees overlap by Dd/2. Thus for m trees trapped the percentage of the waterway area which is blocked is

$$\%Blockage = \frac{m(\frac{1}{2}\pi Db^2/4)}{LsC} \times 100\% \quad (1.25)$$

Having estimated m and knowing Db the increase depth of water (wd) at the bridge is assumed to be

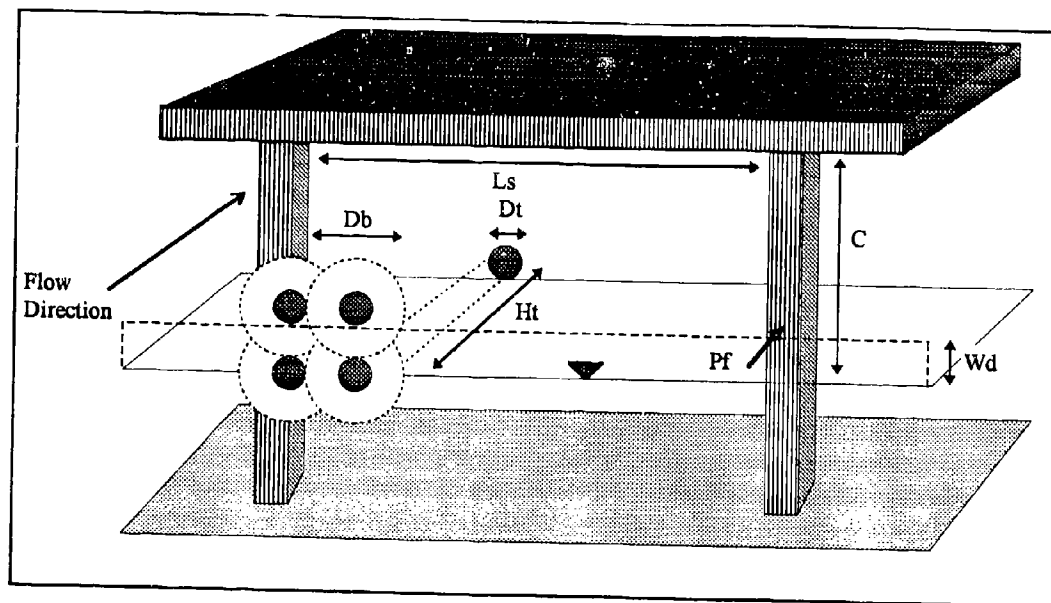
$$\Delta wd = \sqrt{mDd / 2} \quad (1.26)$$

The blockage generates a pressure force (Pf) which acts normal to the bridge is

$$Pf = \frac{1}{2}\gamma \cdot mDb^2 / 4 \quad (1.27)$$

γ is the specific weight of water.

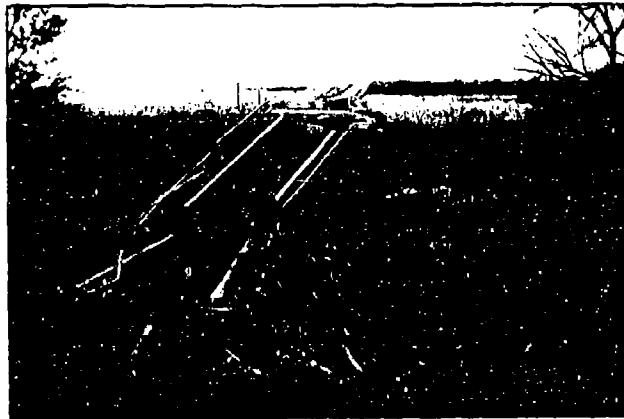
Figure 2.5 Schematic diagram of debris accumulation at bridge piers



2.5.2 Reported Instances of Debris Related Bridge Failure

A study by Parola, Fenske & Hagerty was initiated to investigate the basin-wide impact of the 1993 Mississippi River Basin flooding on damage to the highway infrastructure. Structural geometry information as well as hydraulic information was collected at two sites where bridges collapsed at least partly as a result of debris loading, and was noted to be a contributing factor in the lateral load and scour of many bridges. Plate 1 shows the Missouri 113 bridge over Florida Creek where floating debris was a key factor in its collapse.

Plate 1 : Bridge 113 over Florida Creek, Skidmore Missouri. Failure due to debris loading. Source : Parola, Fenske & Hagerty (1994).



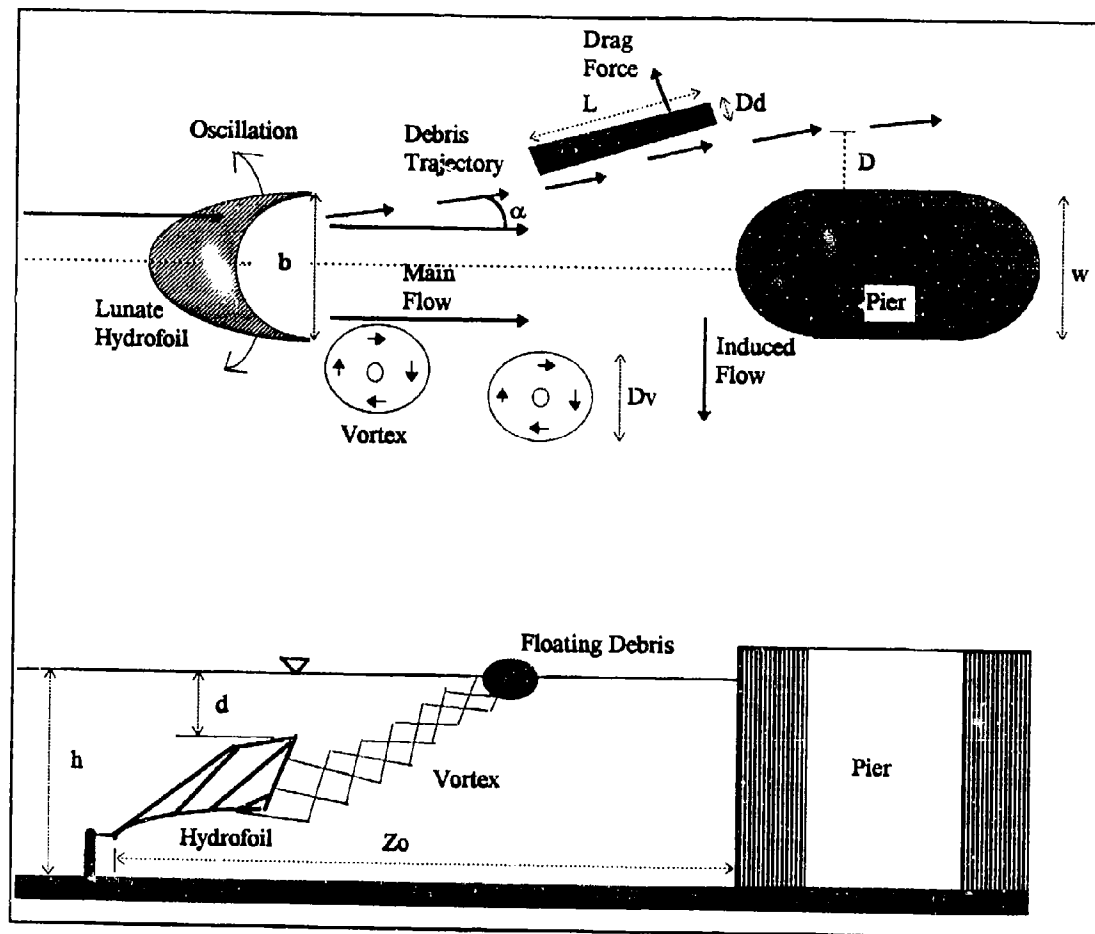
2.5.3 Methods for Managing Floating Debris at Bridges

Only one paper has been found that directly addresses debris management at bridges. Saunders & Oppenheimer (1993) believe that conventional methods of protecting piers from floating debris are inadequate. They comment that the use of pilings or some other barrier upstream of a bridge can actually exacerbate the problem because the debris accumulated may be released at once as a raft which cannot pass under the bridge. They describe a novel deflector, a lunate shaped hydrofoil which generates counter-rotating streamwise vortices in its wake positioned below the surface so that it is not impacted by debris upstream of the piers and so that the vortices migrate to the surface ahead of the pier. The principle is that the near surface flow induced by the vortices deflects debris safely around the pier. Figure 2.6 shows the hydrofoil in elevation and planform. The foil is mounted on a tether or pylon at a depth, d , below the surface and a distance, Z_0 , upstream of the pier and is inclined at an angle such that the force on the foil is downwards and the reaction on the water causes a local motion upwards towards the surface. After interacting with the vortex, debris is deflected at the angle, α , and is displaced sideways by a distance, D , by the time it reaches the pier.

A flume model constructed by Saunders & Oppenheimer indicated that the vorticity remains highly concentrated for a distance of about 20 times the span of the hydrofoil, b , when $b=0.6xh$ (depth of flow). The problem is characterised by a bridge pier width w and by the size of the debris. An average debris size is utilised with diameter D_d and length L . The vortex produced by the device has a characteristic diameter, D_v , of order b (hydrofoil span). If $D_d > D_v$ then the vortex will not impart a net motion to the debris, so they recommend a value of $b > 2D_d$ or $b = w$ (pier width) as, they assume, the majority of debris will have a diameter less than the pier width and this scaling will ensure that the vortex is positioned correctly with respect to the pier. It is also suggested that the device be tethered so that it can oscillate transversely to the flow, so that the vortices will tend to destabilise any debris that might have accumulated on the face of the pier.

In flume tests the hydrofoil is reported to work very effectively and the device would appear to offer a possible approach to managing floating debris at bridges. However, if the average debris length is greater than the pier spacing debris floating with their long axis transverse to the flow are still likely to be trapped and the vortices might even turn flow parallel debris through 90 degrees so that they become jammed between adjacent pier faces.

Figure 2.6 Hydrofoil debris deflector



2.6 DEBRIS CONTROL AT LOCKS, DAMS AND WEIRS

2.6.1 Introduction

Floating debris can create severe problems for a variety of structures and water based activities. Debris can destroy the propellers of recreational and commercial boats and cause damage to boat hulls. Navigation lock operation can be impaired by debris caught on a gate sill. Floating debris has the greatest economic effect on users of large quantities of water such as hydro-electric and thermal electric generating plants and municipal water systems. On occasion dam gates can become stuck partly open by debris intrusion and severe downstream bed scour may occur. Users must therefore install devices to prevent floating debris from entering and damaging their turbines, valves, gates, and pumps. These devices do however cause a slight reduction in intake capacity and are themselves susceptible to impact damage from large debris. Floating debris can also damage the upstream slopes of dams through wave action which hammers debris against the dam wall and other structures.

The following review of floating debris problems and control systems makes use of two REMRR (Repair, Evaluation, Maintenance and Rehabilitation Research Program) reports authored by R. E. Perham, and titled "Elements of floating debris control systems" (1988), and "Floating debris control ; a literature review" (1987) .

Floating debris enters water courses through the following mechanisms.

a) Wind and wave action

On lakes and large rivers waves erode the shoreline causing trees to topple into the water. Structures such as docks can be smashed by waves, and much of the flotsam can remain in the water. Wind and wave action can also cause the removal of debris from natural storage areas such as bays and coves. Wind throw is a major source of

debris input in streams in forested areas and wind has also been known to carry appreciable quantities of sagebrush and tumbleweed into rivers in the western USA

b) Ice Break-up

Moving ice in the spring break-up can increase the undercutting of riverbanks, and trees can be damaged and broken by the force of moving ice.

c) Forest Litter

A larger litter input is derived from leaves from deciduous trees and some conifers. Forest litter is usually protected by the tree canopy during summer and by a snow layer in the winter, however in early spring trees are without leaves and heavy rains will wash the litter away.

e) Forestry Practices

Forest lands soak up large quantities of water and reduce floods and erosion that bring floating debris to the streams and rivers. If a generous ground cover is maintained during tree harvest and roads are made erosion resistant, forest land can still protect the watershed. The harvest of trees on a reasonable schedule will reduce the number of dead trees that may fall into the streams and rivers.

f) Debris Jams

Debris jams may be moved en-mass by a large flood flow or they may be broken down over a long period of time by natural effects such as decomposition.

g) Beaver Dams

The quantity of debris brought into streams by beavers is unknown, but may be a substantial proportion of the total load in some watersheds.

h) Man-made Materials

This includes decaying wooden structures such as piers and wharves, and organic and synthetic material from dumps improperly located along water bodies, and general littering.

2.6.2 Collecting Floating Debris

A) Natural Features

Key debris create jams which are natural stores of large quantities of potential floating debris. Debris also accumulates in small bays and sloughs when water currents and winds are directed favourably.

B) Fixed Structures

Baffle Walls: This is a vertical wall placed in front of an intake structure to intercept debris and thereby reduce impact loads on the intake debris rack. The wall extends several feet below the water surface. Trash rack cleaning and removal is done in a space between the baffle wall and the intake structure.

Dikes : Vane dikes can be used to guide debris into a holding boom or other collection structure, and are placed, for example at China Bend on the Columbia River, on the outside of bends where debris has a natural tendency to move to.

Trash Struts : Trash struts are beams placed in front of an intake in an open framework so that large debris, such as whole trees, will not enter water conduits.

Trash Racks : These are probably the single most important debris control device. The rack is faced with a series of vertical parallel bars to facilitate cleaning. The rack face usually has a slope to facilitate raking.

C) Moveable Structures

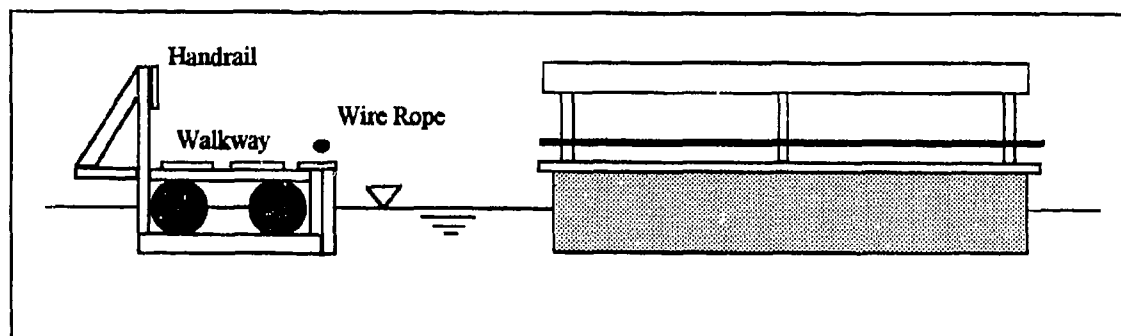
Booms : Booms are a chain of logs, drums, or pontoons secured end to end, floating on a reservoir so as to divert debris. Figure 2.7 shows an example of a log boom

Retention Boom : These are located and sized to hold debris inside or outside an area.

Deflector Boom : The deflector boom is a line of floating elements set at a steep angle to the river currents. Debris is moved along the smooth face of the boom by the hydraulic drag of the current. Debris is then moved laterally to a holding pond where it is eventually removed. They are also used to route debris around structures such as docks, and to keep it away from intakes.

Nets : Nets are used to collect and hold debris.

Figure 2.7 Double Log Log Boom



2.6.3 Removing Floating Debris

Floating debris is removed from water bodies by a variety of machines and manually operated tools, which often takes the form of existing equipment which has

been modified in some manner so that it can handle debris better. For example, the welding of teeth onto a clamshell bucket to give a better grasp of debris.

In addition to equipment modifications, techniques have been developed that make the removal process more efficient or less troublesome. For example, when a trash rack is being raked, the flow through the unit that it protects is reduced or completely stopped. Debris is then easier to remove from the bars. Many techniques have been developed for site specific reasons, such as the continuous removal of debris as it is carried to a dam by high spring flows because when flow slackens the prevailing wind can blow the debris all over the pool.

The following is a list of the most common equipment used for floating debris removal.

a) Trash Rakes :

Hand Rakes : This is an implement with projecting tongs used to remove small debris from trash racks of small hydroelectric plants and other small water intakes. The rake itself is a good tool, but the process is labour intensive.

Shoreline Rakes : Floating debris stranded along the shoreline may be collected with some efficiency with a special rake on a crane-operated dragline. The debris is collected from around the anchor site into one spot and a set of log tongs or a clamshell is used to lift the debris into a container.

Self-powered Trash Rake : A variety of self-powered trash rakes are used to clean debris from trash racks. In a typical system a gantry crane is driven to a specific trash rack, the rake lowered by drum hoist down through the debris accumulation and the raking bottom shelf opened automatically. At the bottom of the trash rack the raking shelf rotates back to the horizontal raking position and its individual fingers reach between the trash rack bars. The rake, raised by cable along up

the face of the rack scrapes off the accumulated debris and at the gantry the debris is dumped into a hopper car or sluiceway.

Gantry crane-operated trash rakes : Hydroelectric plants have an intake gantry crane that moves along rails on the forebay deck from one end of the plant to the other. It can support many essential functions including trash raking.

b) Cranes and Hoists : a wide variety of cranes and hoists, in conjunction with buckets, tongs and grapples can be used to remove debris from the face of dam walls.

c) Loaders : In the situation where floating debris is deflected by booms into holding areas that can be drained, debris can be loaded into trucks using crawler or wheel type loaders.

d) Conveyors : There are several types of conveyor that can be used to lift material from the water to a disposal unit. An appropriate conveyor is the flight conveyor which has scrapers mounted at intervals, perpendicular to the direction of travel, on endless power-driver chains operating within a trough. The main problem with a conveyor is feeding material into it. A variety of techniques have been used to overcome this however, including high pressure nozzles to push debris, propellers to draw water through the conveyor, and men using pike poles.

e) Boats : Multipurpose workboats can be used to tow roundup booms, shove debris along a boom or flush it away from some location with propwash. There are also a number of specially designed debris collection boats in operation in the USA for example, the USAED boat used in San Francisco Bay. This boat has twin bows with a large space in between where a chain net is positioned as a scoop. An onboard crane is used to set a full net on the deck and to replace it with an empty one.

f) Travelling Screens : A travelling screen is a flexible screen surface that moves like a conveyor belt, or it is a rotating perforated drum. The screen blocks the

water intake so that water must flow through it. The screen moves slowly up into a location where the accumulated debris is removed by water jets. The device is used to good effect in the English land drainage and pumping systems which carry a lot of grass and small debris.

g) Air Bubblers : An air bubbler is used to remove small-sized debris from vertical trash racks at the Wider Dam, on the Connecticut River, USA. It consists of a horizontal brass pipe with multiple holes, anchored at the bottom of each trash rack and fed from a compressed air tank. The intake water flow is stopped prior to the air being discharged and the debris rises to the top where it passes over a submersible gate.

2.6.4 Debris Passage

Debris can become a hazard to the operation, if not the integrity, of a dam. To avoid problems of this nature at many hydrodams, the appropriate gate or gates are opened to the necessary height or depth to send the floating debris down stream.

Dam gates: Dam gates can be raised to flush debris downstream provided this action does not cause scour downstream of the dam. However, because debris floats on the surface gates, in general, must be raised a substantial distance to achieve the water velocities needed to take the debris down and through the opening.

Logways/sluceways: Many dams in areas where logging is an important industry, such as the north-western United States and Canada, will contain logways and sluices for passing logs and pulpwood through the structure. The logway is mainly a sloping flume through which water flows to carry the logs to a point below the dam. The passage may contain a conveyor system.

2.6.5 Disposing of Debris

a) Useable Materials

Structural Materials: Some logs may be large enough for structural applications, if the logs are in good condition.

Firewood: In general, a fair portion of debris can be dried and cut up for firewood, but the extent of its usefulness depends on how clean it is.

b) Unusable Materials

Useless debris should be discarded in a locally acceptable manner.

Burning: Debris may be burnt on land or on the water. Debris can be brought ashore by workboat and bag boom or similar scheme where it is lifted out and piled on the ground to be burned. Floating debris can also be burned on water, where permitted, using a barge and an air-curtain burner. If burning is prohibited by local regulations, disposal can be accomplished by burial in suitable locations near the collection sites. Debris should never be placed in areas where it may be carried away by stream flow or where it blocks drainage of an area.

2.6.6 Summary

Floating debris build-up is a continual problem at locks, dams, bridges and water intakes and even causes disruption of water based recreation activities. As a consequence debris control systems have been developed, which are often site specific, that incorporate various collection, removal and disposal elements. These systems are, inevitably, costly to implement.

However, in order to develop a cost effective debris control system at a new structure it would be beneficial to have some understanding of the debris dynamics within

the relevant catchment area, upstream of that structure. For example McFadden and Stallion (1976) undertook a study for the Alaska District Corps of Engineers, to determine the amount, source, and content of debris on the river, and the magnitude of water levels which could cause a substantial debris movement. Also, of particular interest were the average size of the debris pieces and their potential for jamming or damaging the outlet structure of the Chena River Flood Control Dam which was being constructed at the time. Their basin-wide studies helped them make more informed recommendations for counteracting log jamming in the dam gates. A system of debris-aligning pilings was advised with the spacing based upon maximum debris dimensions encountered on the river, and a back-up hoist with clam-shell bucket to remove logs that might manoeuvre into a jamming position. A cable boom system was rejected on the grounds that it was not as easy to clean as the gates themselves and presented a hazard to navigation.

2.7 MANAGEMENT STRATEGIES

A comprehensive study of coarse woody debris in relation to river channel management has been carried out by Gregory & Davis (1992). They collated the findings of 22 papers, many of which have been cited above, and produced a preliminary list of management criteria with regard to debris jams. Appendix B shows Gregory & Davis' table of literature and the authors' findings which form the basis for the treatment of management options here.

Prior to 1970 there was a general consensus that all debris should be cleared from channels, but after that date it was acknowledged that there were advantages to be gained by maintaining debris accumulations.

Arguments for debris removal include :

- a) To improve navigation
- b) To increase channel conveyance by reducing roughness
- c) To eliminate bank erosion
- d) To facilitate the migration of fish, especially salmon (after MacDonald, 1982).

Evidence that debris should remain in place is quite convincing, however, and, for example, Gregory & Davis' study (1992) in the New Forest (U.K.) led them to the conclusion that debris removal was, on the whole, undesirable. (Figure 2.8.). It should be noted, however, that this study, as with most others cited, was carried out in an essentially stable, equilibrium channel environment, where changes to channel morphology are negligible and significant impacts relate mostly to ecological habitat diversity.

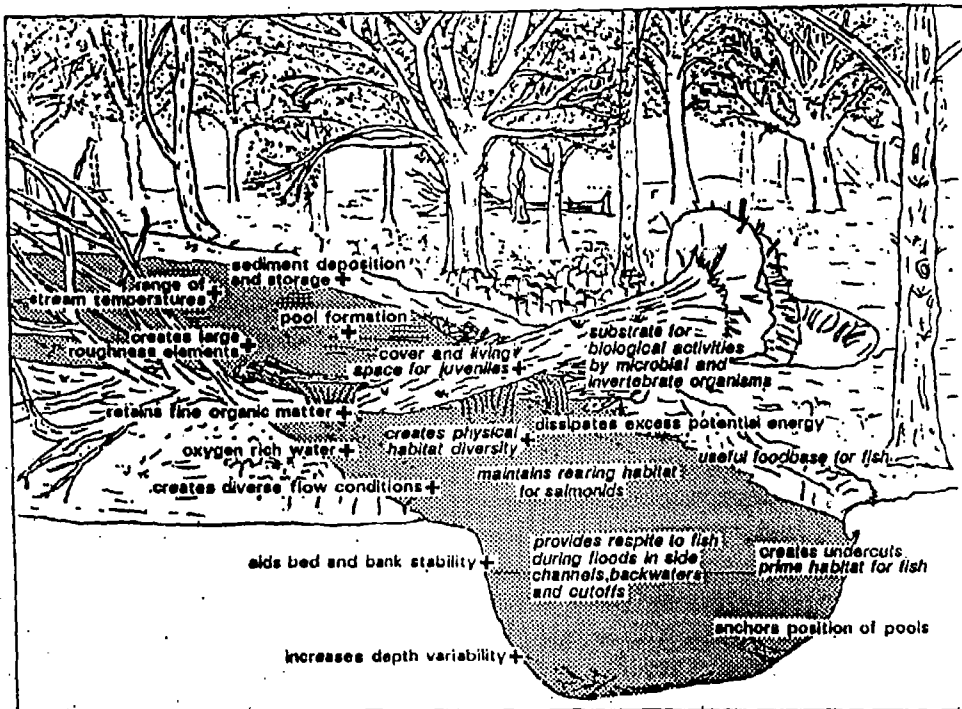
The effective debris management strategy depends on the underlying aim in terms of:

- a) improving drainage
- b) flood mitigation
- c) navigation
- d) enhanced fish migration, or

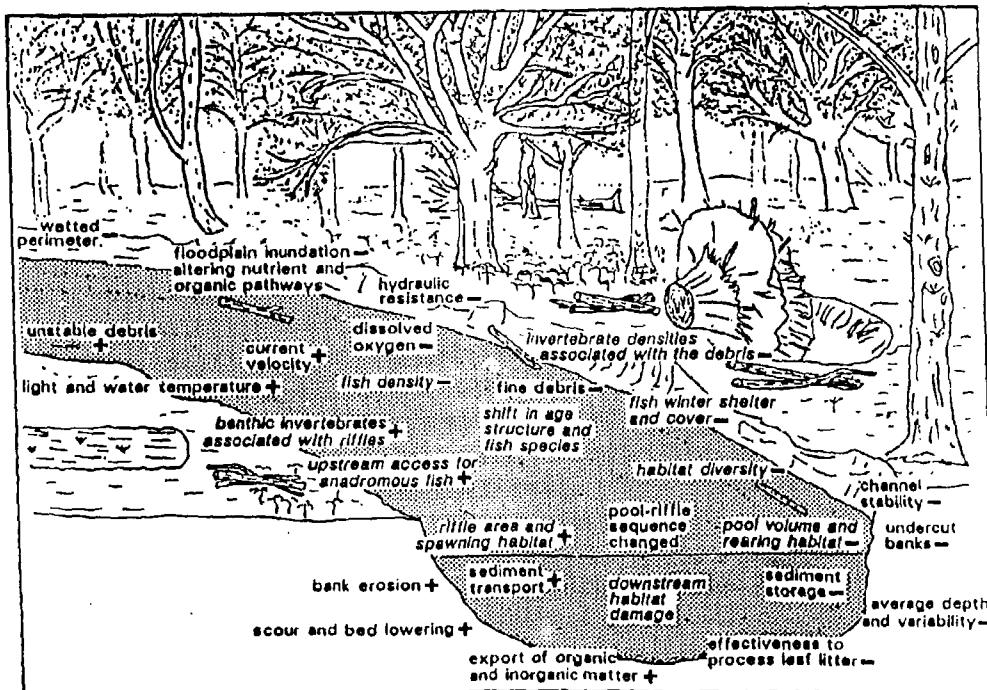
The Significance of Coarse Woody Debris Dams for Channel Morphology, Channel Processes & Ecology

Figure 2.8

DAM PRESENT



DAM REMOVED



Characteristics which relate to ecological habitats are shown in italics

Reproduced by permission of John Wiley & Sons Ltd. (after Gregory & Davis, 1992)

e) improved aesthetic qualities.

Gregory & Davis cite three aspects of hydrogeomorphology (after Coburn, 1989) relevant to an analysis of channel management:

- 1) It is necessary to know the relationship between river channel processes and river channel morphology;
- 2) It is necessary to be aware of the timescales over which river channels may adjust;
- 3) It is necessary to consider channel management in the context of river basin management.

More specifically, debris management must consider :

- 1) Channel stream power characteristics;
- 2) Sediment movement and storage relationships (high/low; fine/coarse sediment; suspended/bedload);
- 3) Channel stability;
- 4) Size and character of river channel in relation to debris size;
- 5) Spacing and frequency of jams
- 6) Size and character of jam, and orientation of component material
- 7) Age and stability of component material.

The management recommendations for woodland areas suggested by Gregory & Davis, are shown in Figure 2.9. They conclude that "... a conservative approach to debris removal should be adopted for most areas, but that different strategies are needed according to the characteristics of particular localities". This statement is all-encompassing but there is no consensus as to the nature of these "different strategies". For example, Gregory & Davis (1992) suggest that, based upon their literature survey, in channels with low stability, no debris should be removed (see figure 2.9). However, this is in direct contradiction to practice in the U.S.A, described by Brookes (1985, pg. 64). "In North America the concept of channel restoration was developed in North

Carolina under the funding of the Water Resources Research Institute of the State University ...Restoration is achieved by removing debris jams and providing uniform channel cross-sections and gradients whilst preserving meanders, leaving as many trees as possible along the stream banks, and stabilizing banks with vegetation and rip-rap where necessary ...".

A similar type of approach, known as stream renovation, has been advocated based on experience on the Wolf River, Tennessee (Mc Connell et al., 1980).

The recommendations of George Palmiter (Institute of Environmental Sciences, 1982) are similar and include the following steps :

- a) Removal of log-jam material by cutting it to a manageable size
- b) Protection of eroding banks using brush piles and log-jam material, with rope and wire
- c) Removal of sand and gravel using brush-pile deflectors
- d) Revegetation to stabilize banks and shade-out aquatic plants
- e) Removal of potential obstructions such as trees and branches

In the light of the literature and these recommendations it was decided to analyze the debris jam/channel morphology relationships with the aim of determining suitable management criteria, because current recommendations and maintenance practices appear to be contradictory.

DETERMINANTS FOR A MANAGEMENT STRATEGY FOR RIVERS IN WOODLAND AREAS

Figure 2.9

| | CHANNEL VARIABLE | MANAGEMENT STRATEGY | | | |
|----------------------------|-------------------------------------|--------------------------------------|--------------------------|-----------------------------|---------------------------|
| | | CHANNEL CLEARANCE | PARTIAL DEBRIS CLEARANCE | NO REMOVAL | LIMITED DEBRIS CLEARANCE |
| CHANNEL ENVIRONMENT | Stream Power | ← high → | | | |
| | | ← low → | | | |
| | Sediment Storage and Transport | ← high → | | | |
| | | ← low → | | | |
| | Channel Width / Tree Height | ← high > 1 → | | | |
| | | ← low < 1 → | | | |
| | Channel Stability | ← high → | | | |
| | | ← low → | | | |
| | Adjacent Land Use Values | high value agricultural | grazing | managed / old growth forest | |
| DEBRIS ENVIRONMENT | Spacing and Frequency of Dams | ← excessive → | ← high → | natural levels | low > 5-10 channel widths |
| | Debris Budget Loading | ← excessive → | ← high → | natural levels | ← low → |
| | Size and Character of Coarse Debris | ← < 10 cm diameter → | | | |
| | | ← > 10 cm diameter → | | | |
| | | ← green foliage → | | | |
| | Size of Blockage | > 10 channel widths long, debris jam | > 5 channel widths long | active debris dam | partial debris dam |
| | Anchorage of Debris | ← no anchorage → | ← single end anchorage → | ← both ends anchored → | |
| | Stability of Debris | ← low → | ← moderate → | ← high → | |
| | Orientation of Debris to Flow | ← 60-90 degrees → | ← parallel to flow → | | |
| IMPACTS | Habitat Diversity | ← low → | ← high → | needs enhancing | |
| | Aesthetics | ← low importance → | ← high importance → | | |
| | Blockage to Fish Migration | ← possible → | ← negligible → | | |

(modified from Gregory & Davis, 1992)

3 RESULTS ANALYSIS

3.1 Method

In preliminary investigations of LWD spatial interpolation analysis was used in order to determine the impact of debris jams in different channel reaches (Wallerstein & Thorne, 1994). While this work offered some interesting results, it could give no indication of the residence time and stability of debris jams, which is a very important factor for determining a debris management strategy. Consequently, in the current research, debris jam sites will be monitored more thoroughly, over time, using re-surveying to pick up changes in the number of jams in each reach, changes in the volume of material in each jam, their impact upon the channel morphology and their residence times, and therefore overall stability, as in-channel geomorphic features.

Site investigations have been carried out in conjunction with the DEC survey crew from Colorado State University, in May and June 1994. Twenty seven DEC channel monitoring reaches were surveyed and significant debris jam site marked off on the thalweg data. Plate 2 shows surveyors at work on Marcum Creek, June 1994. This has given a comprehensive data-set in terms of range of drainage basin areas, channel characteristics (stable/unstable, channelled/natural) and riparian land-use types (agricultural/forested). Figure 3.1 shows a geological map of Mississippi with the DEC project area marked, and Figure 3.2 shows a more detailed site location map.

Reaches on the following creeks were surveyed :

| | | |
|----------------------|------------------------|----------------------|
| Nolehoe Creek | Sarter Creek | Lick Creek |
| Bumey Branch | James Wolf Creek | Long Creek |
| Sykes Creek | Hotopha Creek | Fannegusha Creek |
| Worsham Creek (East) | Worsham Creek (Middle) | Worsham Creek (West) |
| Abiaca Creek | Harland Creek | Red Banks Creek |
| Otoucalofa Creek | Coila Creek | Lee Creek |
| Perry Creek | Hickahala Creek | Marcum Creek |

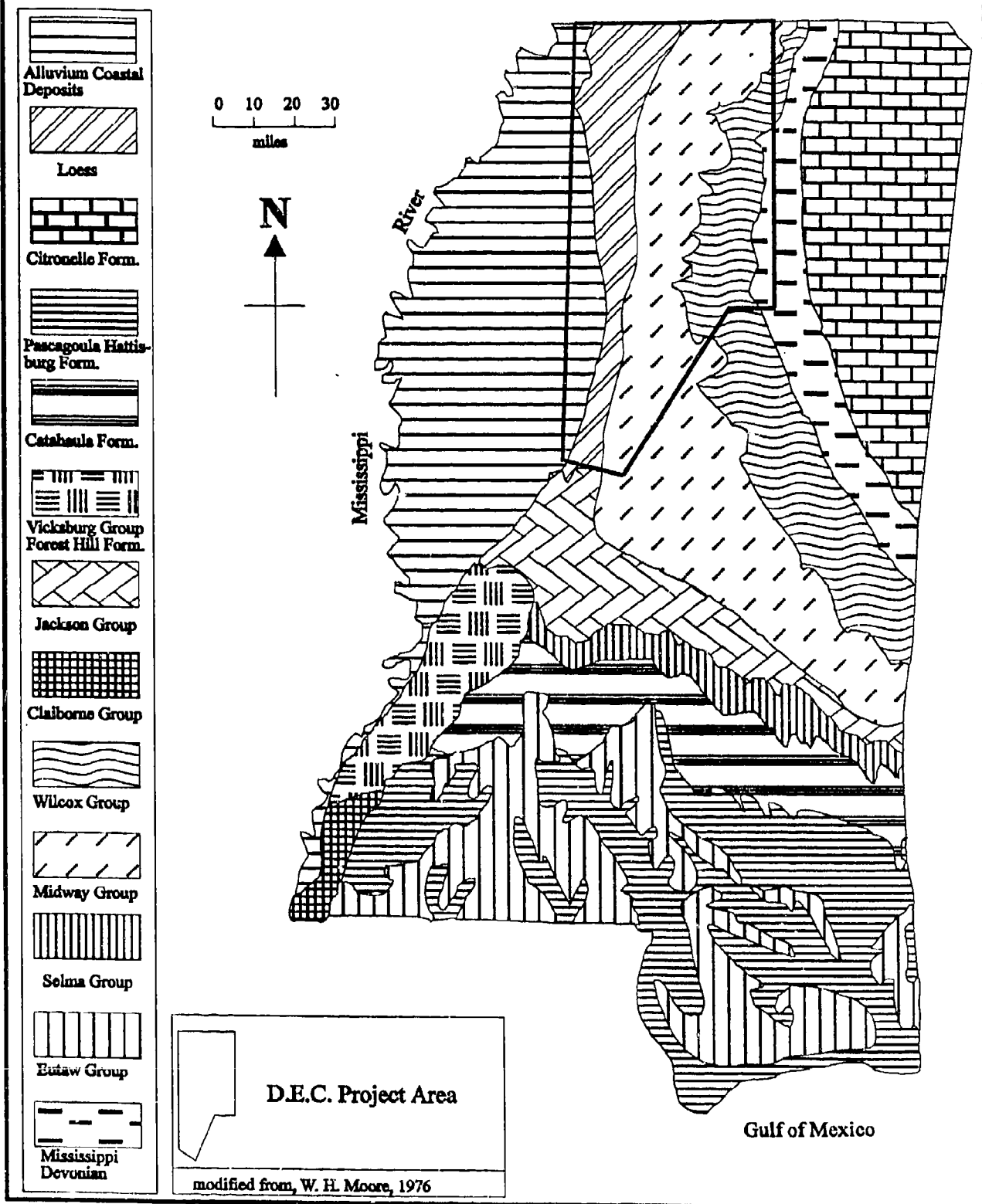
A full description of the DEC monitoring site characteristics is given in the CSU DEC project site evaluation reports (for example, Watson et. al., December 1993).

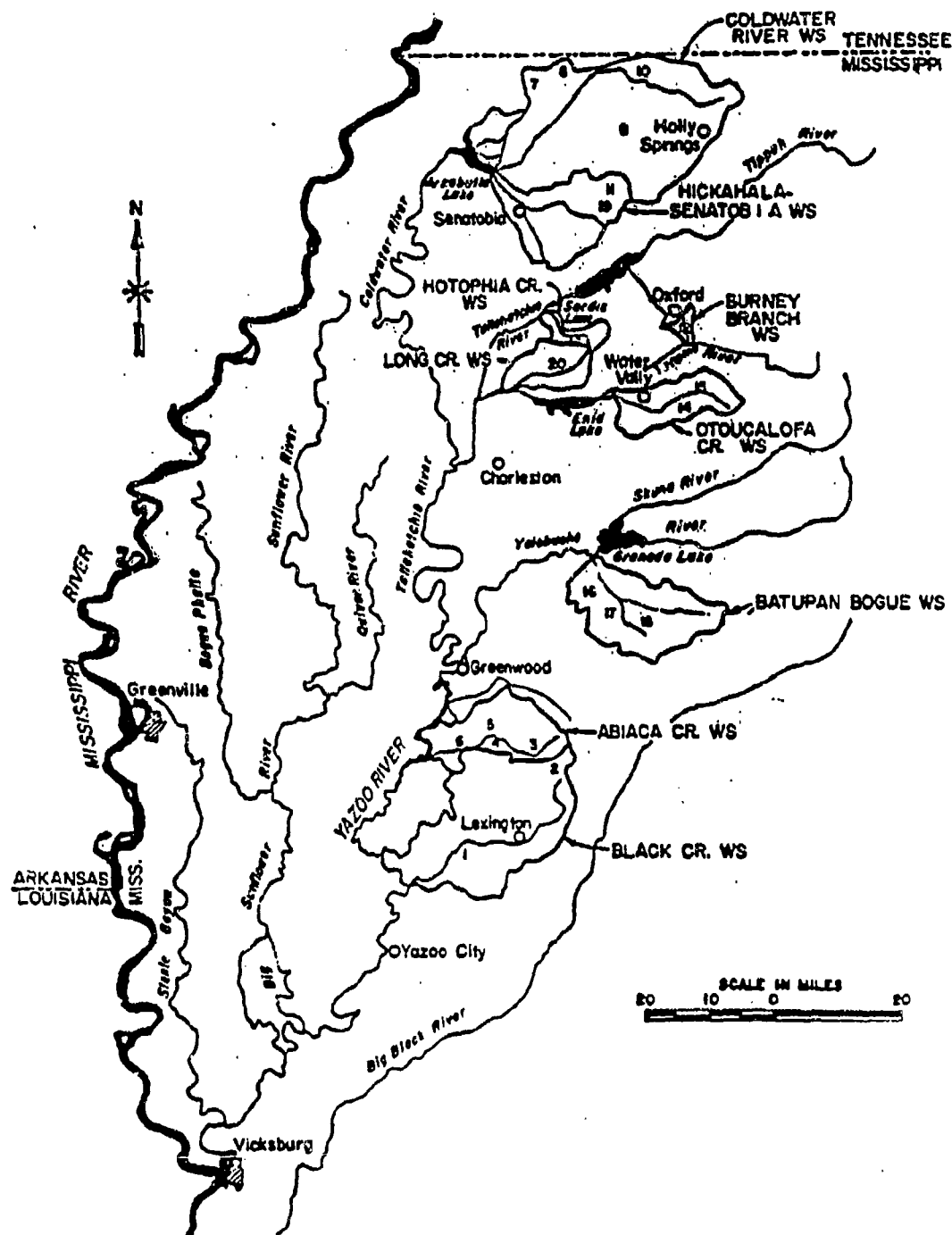
Data sets obtained from each reach consist of channel thalweg profiles, with significant debris obstructions surveyed into each profile.

Geomorphological reconnaissance was carried out at each jam site to characterise the jam and its' impact upon the channel. Appendix D shows the field reconnaissance sheets used in this study.

The survey data has been processed to obtain reach planforms and long profiles for each creek which will now be monitored over a number of years using the future DEC semi-annual re-surveys of each reach. Geomorphological data has been entered into a windows based Quatro-Pro data-base which can easily be assimilated into the DEC project work.

GEOLOGICAL MAP OF MISSISSIPPI SHOWING SURVEY SITES Figure 3.1





(modified from Raphelt et al., 1995)

3.2 DATA ANALYSIS

3.2.1 Site Geomorphology and debris jam characteristics

Refer to Figure 3.3 , and Tables 1 and 2.

a) The relationship between reach drainage area and the number of debris jams per 1000 ft of channel is shown on a semi-log plot in Figure 3.3. This negative relationship has a statistically significant r^2 value (0.72) indicating a strong correlation between the variables. This trend suggests that in small channels (smaller drainage area) jams form where large trees ("key debris") fall across the river. As channel size, and therefore flow competence, increases however so larger woody material can be moved downstream and dispersed and thus fewer coherent jams form. Debris in larger channels becomes aligned flow-parallel and is often deposited on the outside of meander bends and also on bars heads where it helps to stabilise and accelerate bar growth. Debris routed downstream in larger channels also has a high potential for becoming snagged at structures such a bridge piers.

b) From Table 1 and Table 2 it is apparent that in six out of the nine creeks where major debris jams were found the channel type has been classified as degradational with knickpoints. This would suggest that the predominant debris input mechanism in these creeks is through knickpoint migration which consequently causes mass bank failure and tree topple.

c) Six out of the nine creeks with jams are sinuous or actively meandering. These include Harland, Abiaca 3 and Abiaca 4, all of which have a high debris load but do not suffer from severe degradation. This evidence suggests that meander migration is another major, spatially predictable, cause of woody debris input to the channel network.

d) Riparian land-use information indicates that, as would be expected, all the debris choked reaches have densely wooded riparian zones, as oppose to urban or agricultural land types, where natural large woody debris input would be virtually eliminated.

e) The Beta values (vertical debris orientation) of major debris jam components shows that, at the majority of sites, material lay flat on the river bed ($\beta = 0$). One exception is Nolehoe Creek where Beta values vary from 0 to 60 degrees probably due to the very steep

banks and incised channel. Many of the large trees here appear to have slid into the channel on rotational slip or slumping bank failures rather than through slab-type topple. See Plate 3.

f) The Alpha values (horizontal debris orientation) show no strong relationship with change in drainage basin area. The average Alpha value is 120 degrees, however, many jams have individual components at 90 degrees to the channel.

g) The relationship between jam-induced flow diversion types (Underflow/Dam/Deflector/Flow-Parallel) and drainage area is indistinct. Larger creeks, such as Abiaca 4 do, however, tend to have more of the Flow-Parallel type jams (due to debris alignment by the greater discharges) while Dam type jams are more common in the smaller creeks such as Hickahala 11. Plate 4 shows a Dam type debris jam on Hickahala Creek (11), Site 3.

h) Influence on flow routing. There is no strong trend for this variable with increasing drainage basin area but on the whole larger channels tend to have more partial jams while smaller channels, such as Nolehoe Creek, tend to have more complete jams. The only active jam found is on Worsham Creek (West) where the flow is blocked by a beaver dam. The water surface elevation is raised by over two feet behind this dam. Plate 5 shows the beaver dam on Worsham Creek (West).

3.2.2 Planform and thalweg survey data

Refer to Figures 3.4a through 3.5v.

Note that planform and thalweg data is not available for Coila Creek, Abiaca Creek (3) and Hickahala Creek (22) due to severe errors in the survey data. Corrected values for these creeks will be obtained from the C.S.U. DEC data-sets once they have been processed. The following creeks have debris jams sites marked:

| | | |
|------------------------|---------------|----------------------|
| Worsham Creek (West) | Nolehoe Creek | Hickahala Creek (11) |
| Worsham Creek (Middle) | Lick Creek | Harland Creek (1) |
| Abiaca Creek (4) | | |

Debris jam sites are identified on all survey plots as triangles with their corresponding site numbers.

a) Planform Plots : Figures 3.4a to 3.5v.

There appears to be no distinguishable spatial pattern of debris jams within each channel reach. Jams are not regularly spaced or associated with any particular form within the channel morphology (such as riffles). At a slightly larger scale, however, it is evident that many jams are to be found on the apex of meander bends against the outer bank probably due to receding flow deposition or because of direct input due to outer-bank undercutting. (See Figure 3.4p, Abiaca 4). There is also no distinguishable difference in debris jam location in each reach moving from channel with smaller to larger drainage areas.

b) Thalweg Plots : Figures 3.5a to 3.5v.

Worsham Creek (West) : Figure 3.5k. There is no discernible bed adjustment (scour or backwater sedimentation) associated with the jam sites.

Worsham Creek (Middle) : Figure 3.5j. There appears to be some bed scour associated with a number of the jam sites. Scour hole depths range from two to four feet.

Nolchoe Creek : Figure 3.5a. The channel gradient here is steep. There appear to be scour holes associated with a number a jams, most noticeably site 7. Also, a raised bed area, upstream of Site 8 is probably an area of backwater sedimentation.

Lick Creek : Figure 3.5c. Three of the four jams in this reach are located immediately downstream of an active knickpoint (upstream of Site 2). Debris input is therefore probably due to local bank failure in the over-steepend reach.

Hickahala Creek (11) : Figure 3.5s. Much of the debris in this creek was lodged against, and had, in places, displaced the recently installed rip-rap embankment.

Abiaca Creek (4) : Figure 3.5o. There is little discernible bed elevation change at either of the jam sites here that can be attributed to the debris jams.

Harland Creek : Figure 3.5l. There appears to be some localised bed scour immediately upstream and downstream of jam site 2 but site 1 appears not to have caused any discernible change in bed elevation.

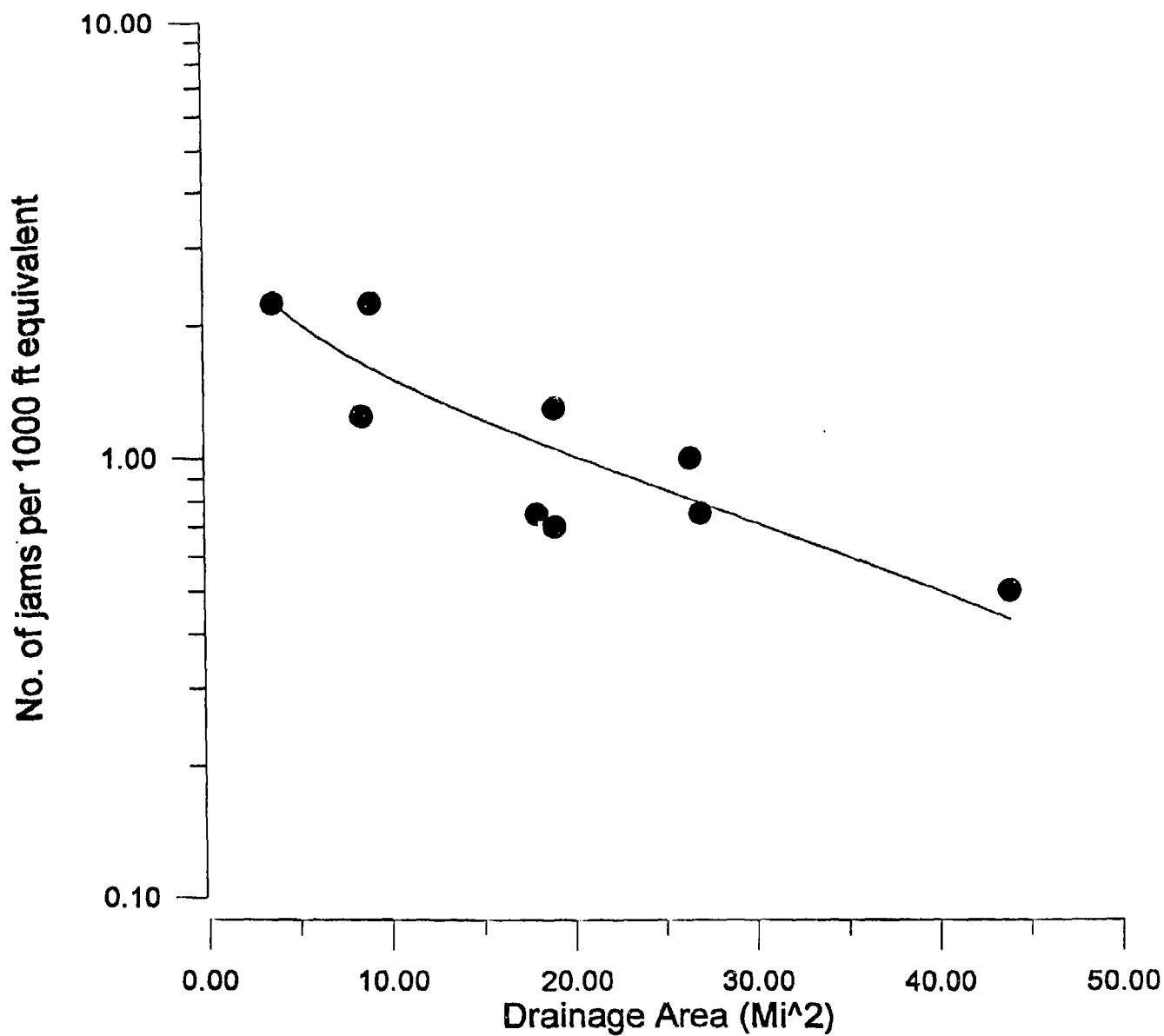
It is evident from these thalweg plots that debris jams do cause localised bed scour, and also backwater/bar sediment deposition. From field observations it appears that jam-

induced backwater sediment deposition is more prevalent where the sediment load contains a large bedload gravel fraction, while in creeks with a predominantly sand grade (and finer) sediment load sediment retention is not so effective probably because the finer fractions remain in suspension and are not "filtered out" by the debris.

There appears to be no distinguishable trend or change in debris jam impact upon bed elevation and sediment routing when moving from creeks with a small drainage area to those with a larger drainage area. However, if creeks with a high woody debris load, such as Nolehoe Creek (Figure 3.5a) or the Worsham Creeks are compared with those that have no debris input at all, such as James Wolf Creek (Figure 3.5e) and Red Banks Creek (Figure 3.5m), it is evident that the latter have far smoother thalweg profiles, even though they have very similar sediment loads and geomorphological characteristics. The irregular thalweg profiles must therefore be due to flow disturbance and sediment retention by debris accumulations. It should be noted that such bed irregularities offer an improved habitat for fish and other aquatic fauna and flora, where an otherwise homogeneous flat sand-bed would offer little diversity.

CHANGE IN JAM FREQUENCY WITH DRAINAGE AREA

Figure 3.3



Fit Results

Fit 3: Log, $Y=B*\log(X)+A$

Equation:

$Y = -0.742883 * \log(X) + 3.24002$

Number of data points used = 9

Average $\log(X) = 2.75356$

Average $Y = 1.19444$

Regression sum of squares = 2.48154

Residual sum of squares = 0.920685

Coef of determination, R-squared = 0.729387

Residual mean square, $\sigma^2_{\text{hat}} = 0.131526$

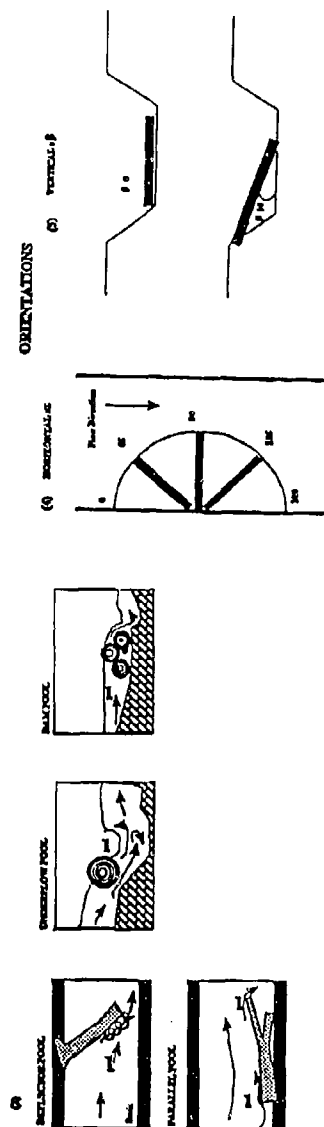
DEC STREAM CHARACTERISTICS

| Creek | Drainage Area | Composite Width | Composite Depth | Composite Slope | Sediment Type | Riparian Vegetation | Channel Stability | Sinuosity | Sediment Transp (t/day) | 2yr Q(cfs) |
|----------------|---------------|-----------------|-----------------|-----------------|--------------------------|--------------------------------------|-------------------------|------------|-------------------------|------------|
| Harland | 27 | 85.2 | 5.88 | 0.00061 | sand/gravel (0.5) | dense wooded | stabilizing | meandering | 35.08 | 3739 |
| Fannegusha | 18 | 73.8 | 7.39 | 0.002 | medium sand (0.31) | dense wood | unstable : head-cuts | straight | 28640 | 3325 |
| Abiaca 3 | 26.5 | 55.9 | 6.5 | 0.00094 | sand (0.25) | wooded | quasi-equilibrium | meandering | 7602 | 3339 |
| Abiaca 4 | 44 | 70 | 3.2 | 0.0016 | sand/gravel (0.49) | mixed wooded (birch)/open | stable | meandering | 1925 | 3760 |
| Colla | 42 | 57 | 3.2 | 0.0019 | sand/gravel (10.00) | dense (birch & willow) | stable | sinuous | 34 | 4780 |
| Abiaca 6 | 99 | 104 | 5.7 | 0.00062 | sand (0.37) | wooded | stable | straight | 1831 | 7095 |
| Notshoe | 3.7 | 36.65 | 4.1 | 0.007 | clay bed / gravel (10mm) | dense wooded | unstable | straight | 1053 | 978 |
| Lick | 8.5 | 49 | 5.41 | 0.0027 | sand | wooded | degrading : knickpoints | straight | 11566 | |
| Red Banks | 27.8 | 108 | 6.3 | 0.00165 | medium sand (0.5) | wooded | degradational | straight | 2518 | 3851 |
| Lee | 7.5 | 107.5 | 6.3 | 0.00165 | medium sand (0.4) | 2000ft us = open, 2000ds = birch | stable | straight | 25185 | 1377 |
| Hickahala | 9 | 44.5 | 5.3 | 0.002 | sand/clay | wooded | knickpoints : unstable | sinuous | 10455 | |
| Burney Branch | 10 | 104.3 | 7.2 | 0.00087 | sand (0.36) | mixed (willow, sycamore, birch) open | stable | straight | 4057 | |
| Lower Hototha | 17.1 | 64.7 | 12.7 | 0.0018 | sand | wooded | degradational | straight | 45161 | 3386 |
| Upper Hototha | 5.4 | 71 | 5.3 | 0.00058 | sand | wooded | degradational | straight | 1249 | 1180 |
| Marcum | 4.7 | 45.1 | 4.4 | 0.0028 | sand | wooded | degradational | straight | 18389 | 1190 |
| Otaucaia | 41 | 89.4 | 8.55 | 0.0011 | sand (0.4) | wooded | degrading | meandering | 27278 | 4617 |
| Sarter | 6.4 | 38.8 | 5 | 0.0024 | medium sand (0.37) | open/shrubs | degradational | straight | 8111 | 1391 |
| Perry | 8.1 | 70 | 6.3 | 0.0026 | sand (0.32) | wooded | degradational | sinuous | 11095 | 1790 |
| Sykes | 122 | 80.8 | 5.49 | 0.0015 | sand (0.34) | wooded | unstable | meandering | 24197 | 2542 |
| East Worsham | 9.5 | 56.67 | 6.15 | 0.0023 | sand (0.31) | wooded | incised / degradational | straight | 20005 | 1935 |
| Middle Worsham | 5.2 | 44.6 | 5.05 | 0.0013 | sand | wooded | incised / degradational | sinuous | 9738 | 1153 |
| West Worsham | 4 | 37.6 | 4.8 | 0.0022 | sand | wooded | incised / degradational | sinuous | 9173 | 1096 |
| James Wolf | 10.8 | 73.25 | 6 | 0.00175 | medium sand (0.35) | open/willows | stable | straight | 10885 | |
| Long | 11.1 | 59 | 3.9 | 0.00188 | medium sand (0.38) | wooded | aggradational | sinuous | 5382 | 2209 |
| Abiaca 21 | | 159 | 9.9 | 0.00024 | sand | wooded | stable | straight | 6414 | |
| Hickahala 22 | | | | | | | | straight | | |
| Harland 23 | | | | | | | | meandering | | |

Table 1

DEBRIS JAM DATA-BASE : MAY 1994

| CREEK | SITE | DRAINAGE AREA | BETA ANGLE | ALPHA ANGLE | FLOW DIRECTION | CHANNEL INFLUENCE | NO. JAMS NO. PER 1000FT |
|----------------|------|---------------|--------------|-------------|-------------------------|-------------------|-------------------------|
| Harland 1 | 1.00 | 27.00 | 0.00 | 180.00 | deflector | partial | 3.00 |
| | 2.00 | 27.00 | 5.00 | >90<180 | underflow | partial | 0.75 |
| | 3.00 | 27.00 | 0.00 | >150<180 | underflow >parallel | partial | |
| Abiaca 3 | 1.00 | 26.50 | 5.00 | >90<110 | underflow | partial | 4.00 |
| | 2.00 | 26.50 | 0.00 | 90.00 | dam>deflector>underflow | complete | |
| | 3.00 | 26.50 | 0.00 | >90<130 | underflow | complete>partial | |
| Abiaca 4 | 1.00 | 26.50 | 0.00 | 90.00 | dam>underflow | active>complete | 1.00 |
| | 2.00 | 26.50 | 0.00 | >90<130 | underflow | partial | 2.00 |
| | 3.00 | 26.50 | 0.00 | 140.00 | underflow>dam | partial | 0.50 |
| Worsham West | 1.00 | 44.00 | 0.00 | >100<180 | deflector>parallel | partial | 7.00 |
| | 2.00 | 19.00 | 15.00 | 90.00 | underflow>dam | partial | |
| | 3.00 | 19.00 | 0.00 | 90.00 | underflow | partial | |
| Hickahala 11 | 1.00 | 19.00 | 0.00 | 90.00 | underflow | partial | |
| | 2.00 | 19.00 | 0.00 | >120<130 | underflow>deflector | complete>partial | |
| | 3.00 | 19.00 | 0.00 | >90<100 | deflector>underflow>dam | partial | |
| Nolehue | 1.00 | 19.00 | 0.00 | 90.00 | dam | active | 4.00 |
| | 2.00 | 9.00 | 0.00 | 90.00 | dam>deflector | complete | 0.88 |
| | 3.00 | 9.00 | 0.00 | >100<110 | deflector | partial | |
| Lick | 1.00 | 9.00 | 0.00 | >90<100 | deflector>dam | complete | 9.00 |
| | 2.00 | 9.00 | 0.00 | 135.00 | deflector | partial | |
| | 3.00 | 9.00 | 0.00 | 90.00 | dam | complete | 2.25 |
| Fannegusha | 1.00 | 3.70 | >45<60 | 100.00 | deflector | complete | |
| | 2.00 | 3.70 | >0<45 | 90.00 | deflector | complete | |
| | 3.00 | 3.70 | 45.00 | >100<110 | deflector | complete | |
| Worsham Middle | 1.00 | 3.70 | >30<40 | 90.00 | deflector | complete | |
| | 2.00 | 3.70 | >25<30 | 90.00 | deflector | complete | |
| | 3.00 | 3.70 | >20<30 | >90<180 | deflector | partial | |
| Fannegusha | 1.00 | 3.70 | >0<40 | >90<180 | dam | active | 5.00 |
| | 2.00 | 8.50 | NOT SURVEYED | | | | 1.25 |
| | 3.00 | 18.00 | NOT SURVEYED | | | | 0.75 |
| Worsham Middle | 1.00 | 5.20 | NOT SURVEYED | | | | 13.00 |
| | 2.00 | | | | | | |
| | 3.00 | | | | | | |



Active : jam forms a complete barrier to water and sediment and also creates a distinct step, or fall in the channel profile

Complete : complete barrier to water and sediment movement, but no significant step

Partial : jam is only a partial barrier to flow

Table 2



Plate 2 : Surveyors on Marcum Creek



Plate 3 : Nolehoe Creek, Site 2. Deflector Jam



Plate 4 : Dam-type debris jam. Hickahala Creek, Site 3



Plate 5 : Active beaver dam. Worsham Creek (West), Site 6

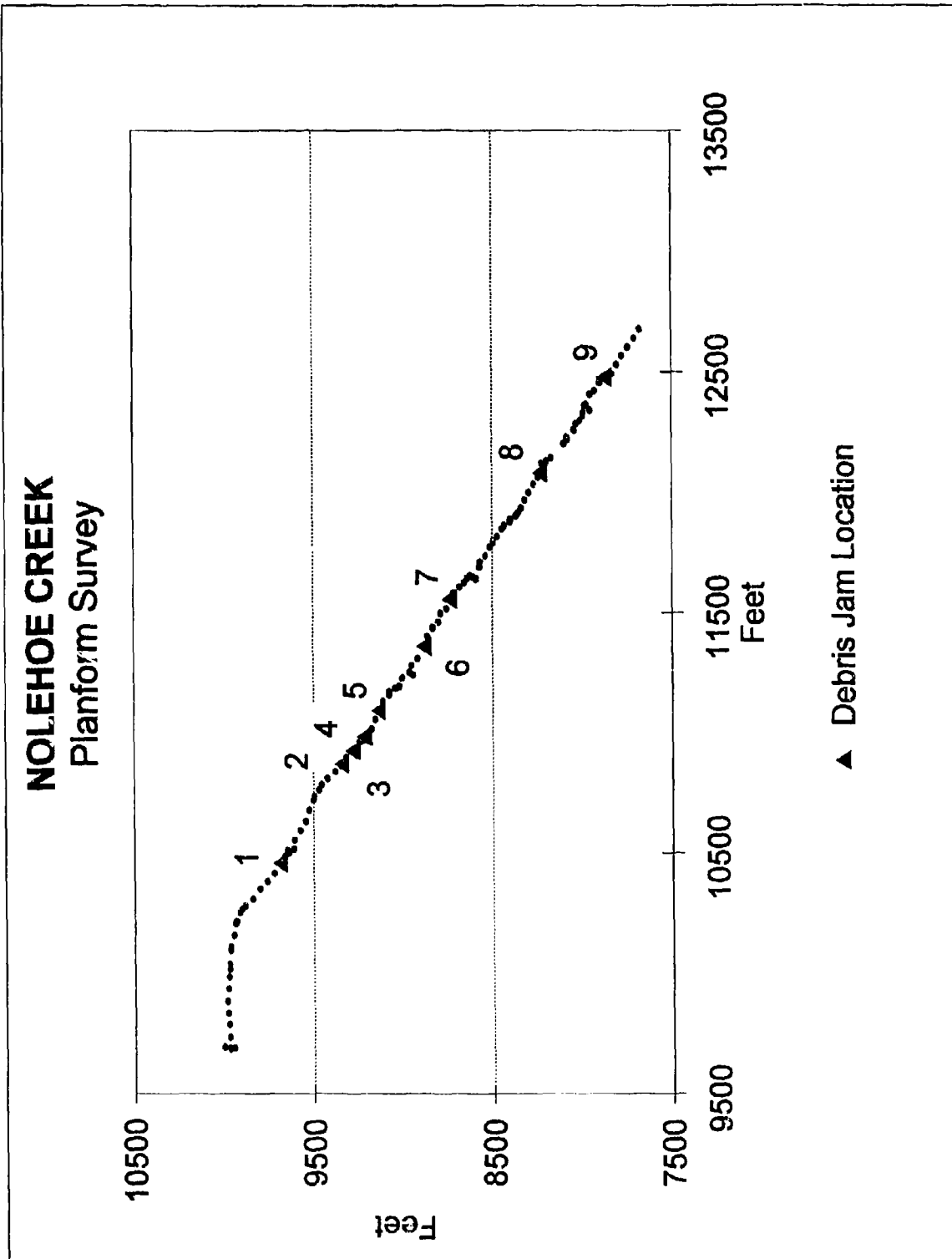


Figure 3.4a Planform of Nolehoe Creek for summer 1994 data.

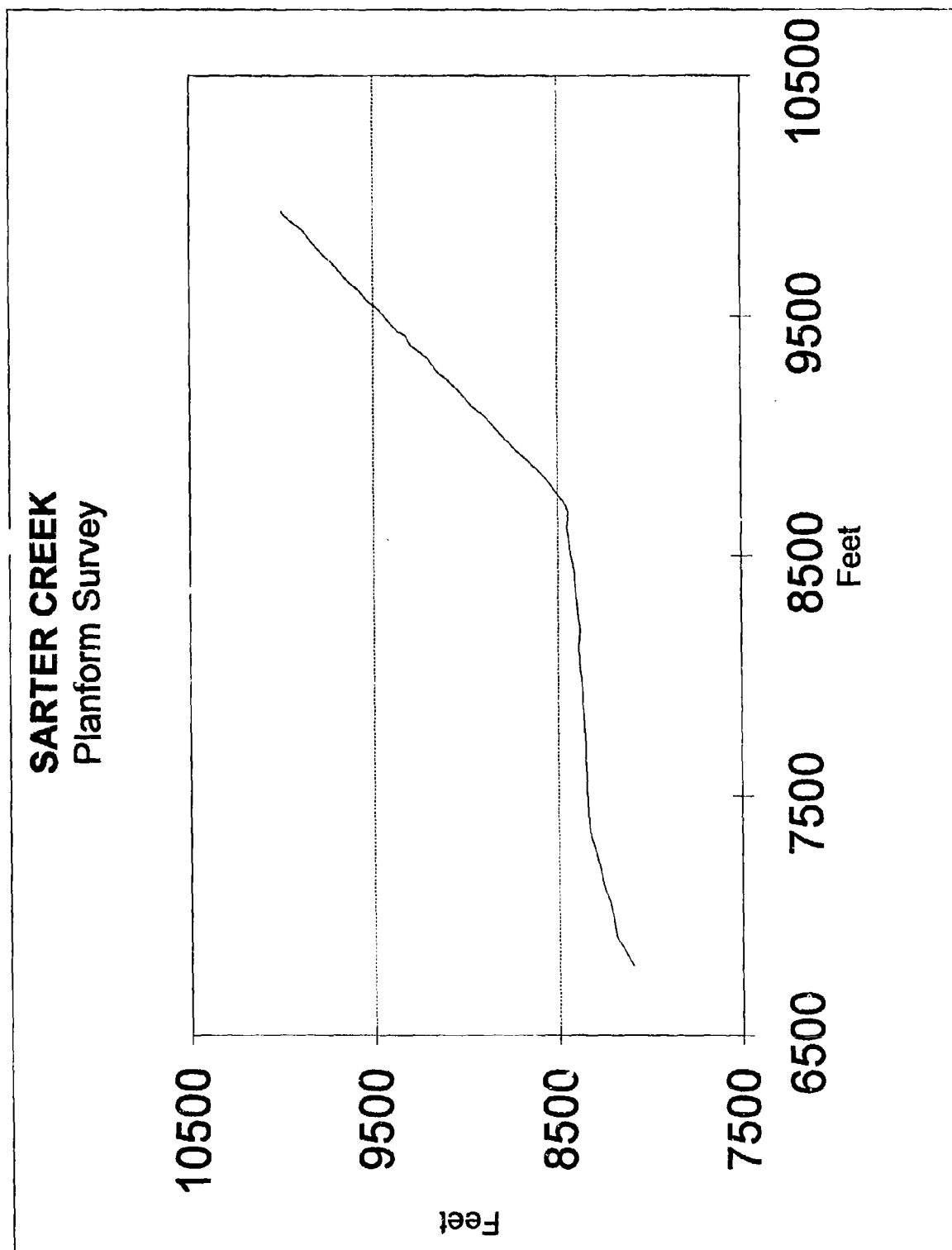


Figure3.4b Planform of Sarter Creek for summer 1994 data.

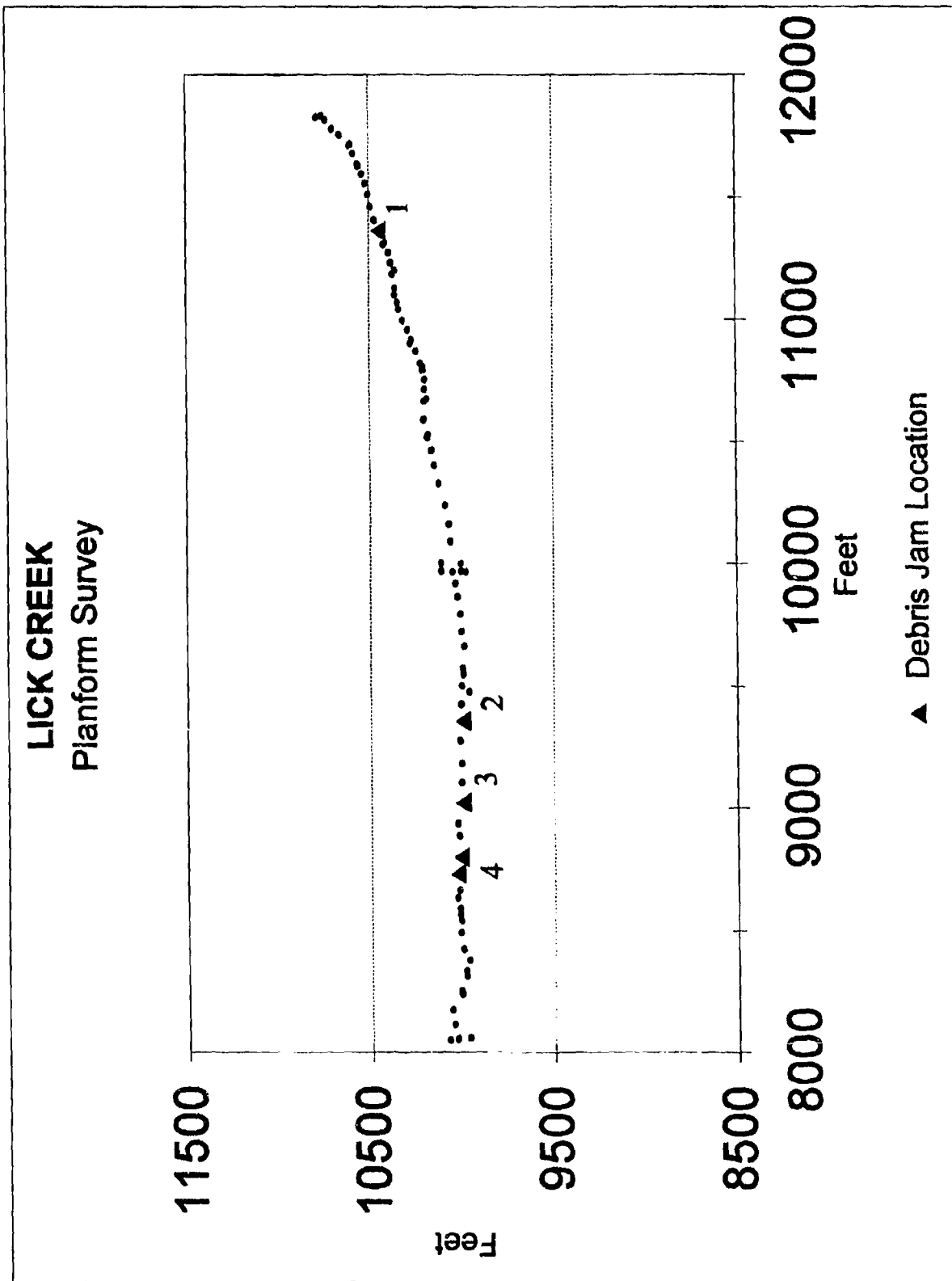


Figure 3.4c Planform of Lick Creek for summer 1994 data.

BURNEY BRANCH
Planform Survey

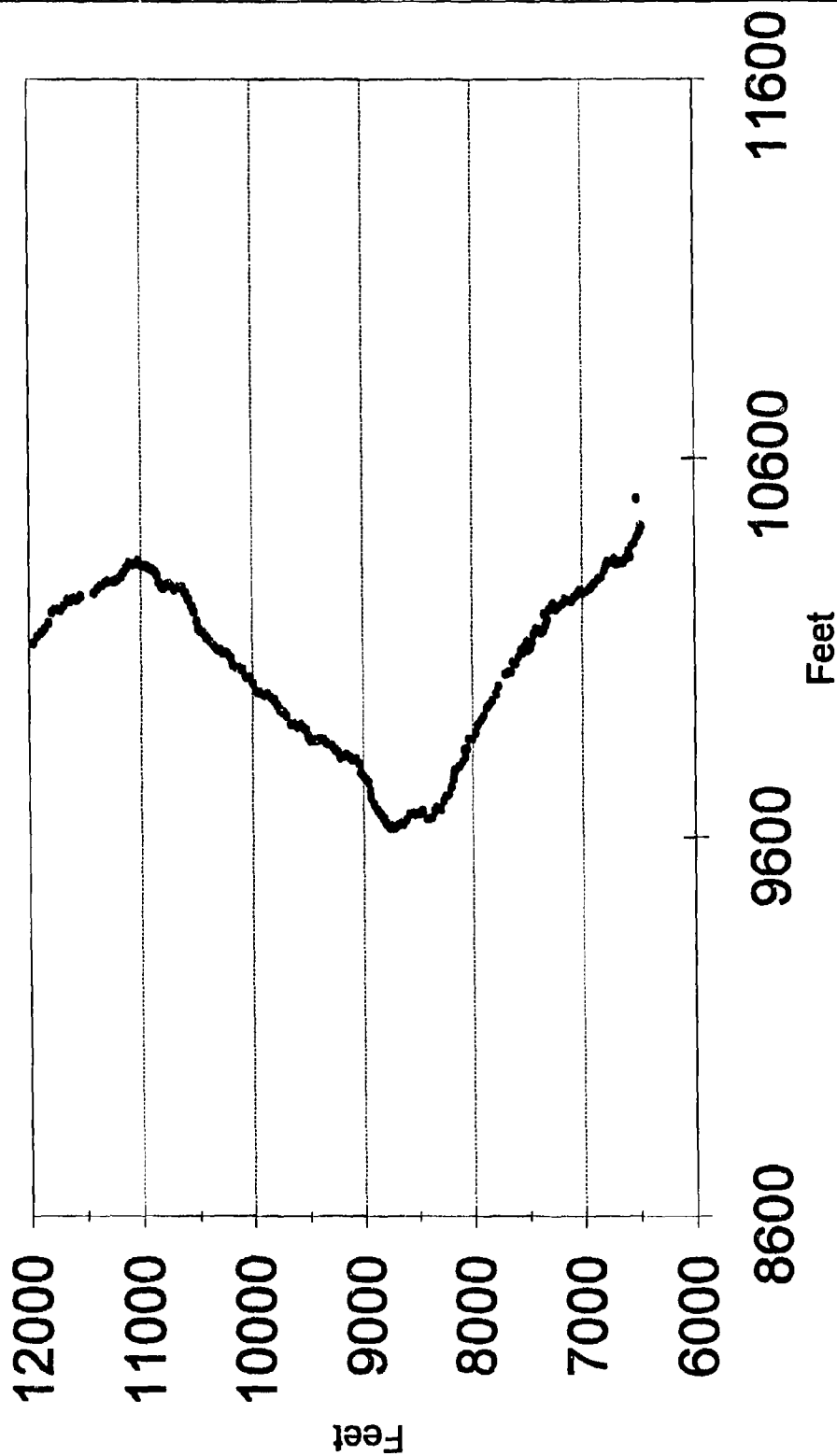


Figure 3.4d Planform of Burney Branch for summer 1994 data.

JAMES WOLF CREEK
Planform Survey

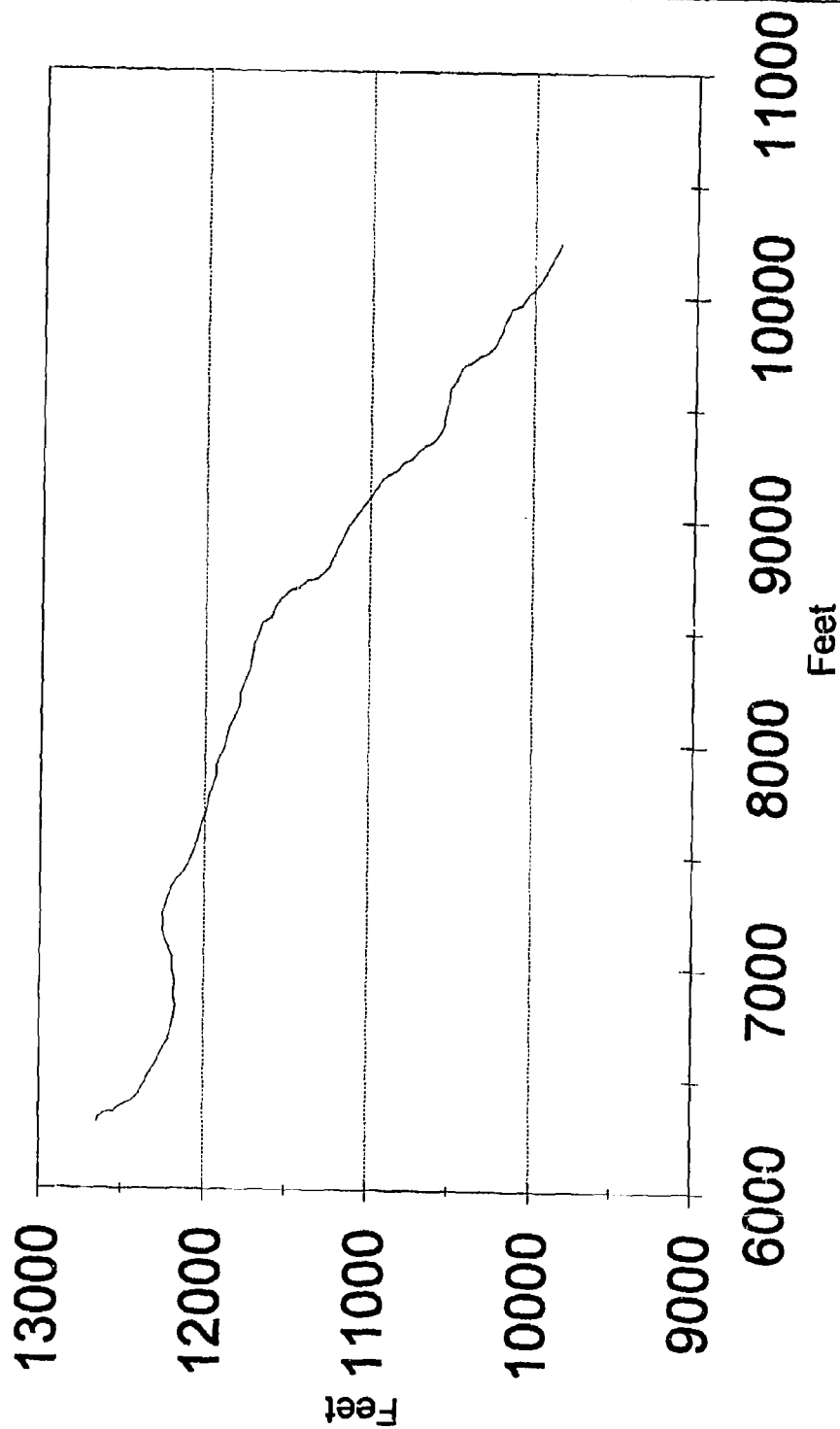


Figure 3.4e Planform of James Wolf Creek for summer 1994 data.

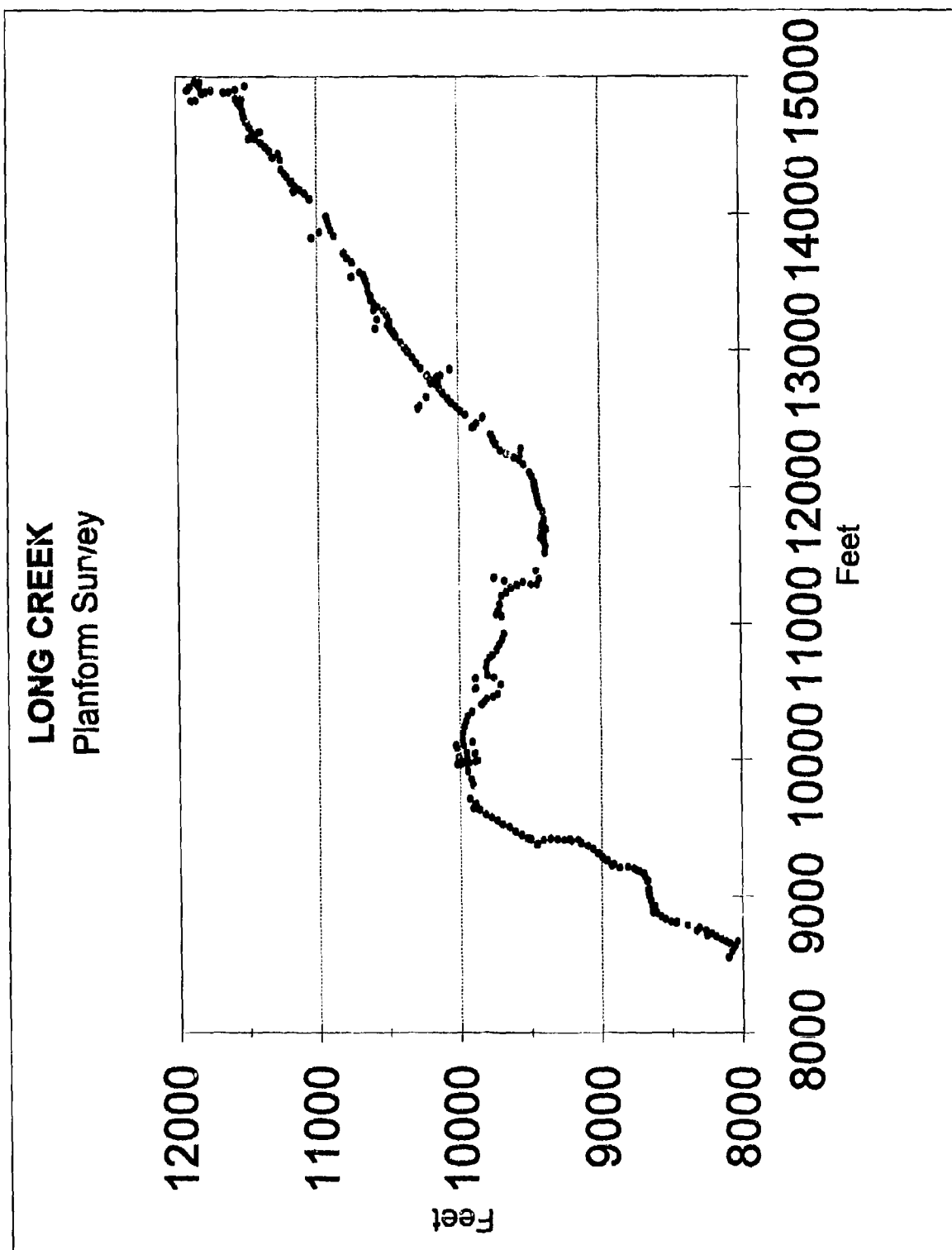


Figure 3.4f Planform of Long Creek for summer 1994 data.

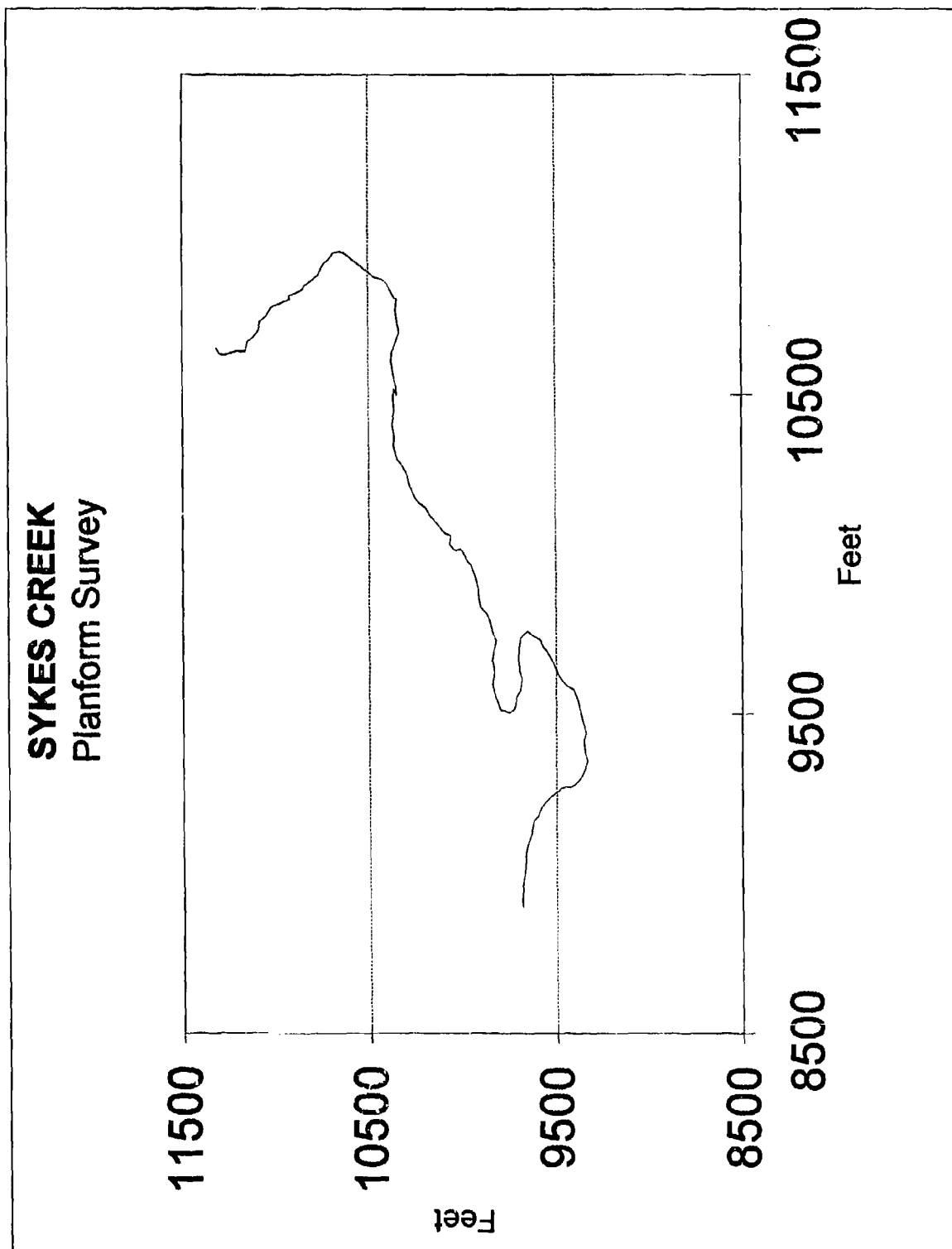


Figure 3.4g Planform of Sykes Creek for summer 1994 data.

HOTOPHA CREEK Planform Survey

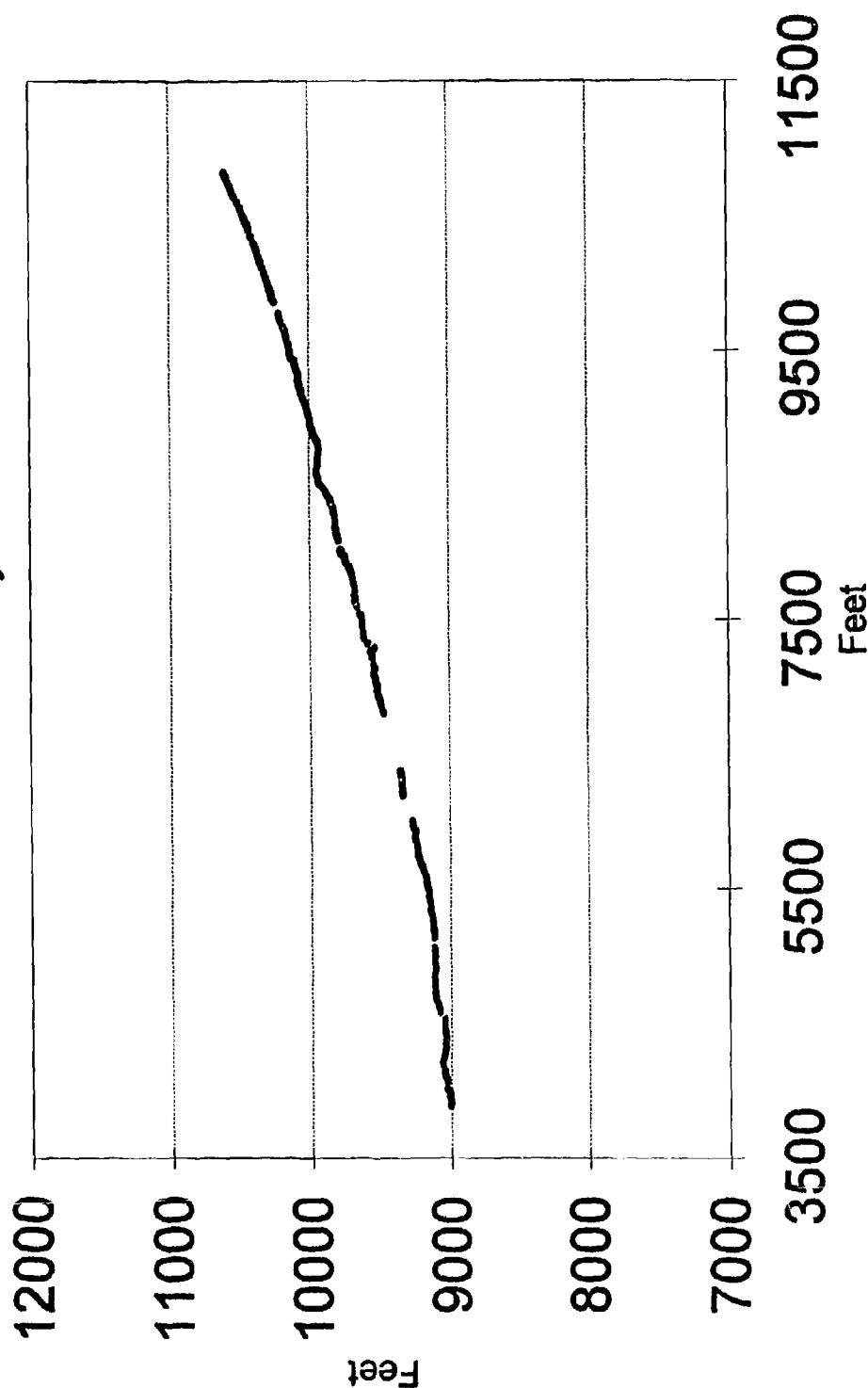


Figure 3.4h Planform of Hotopha Creek for summer 1994 data.

FANNEGUSHA CREEK Planform Survey

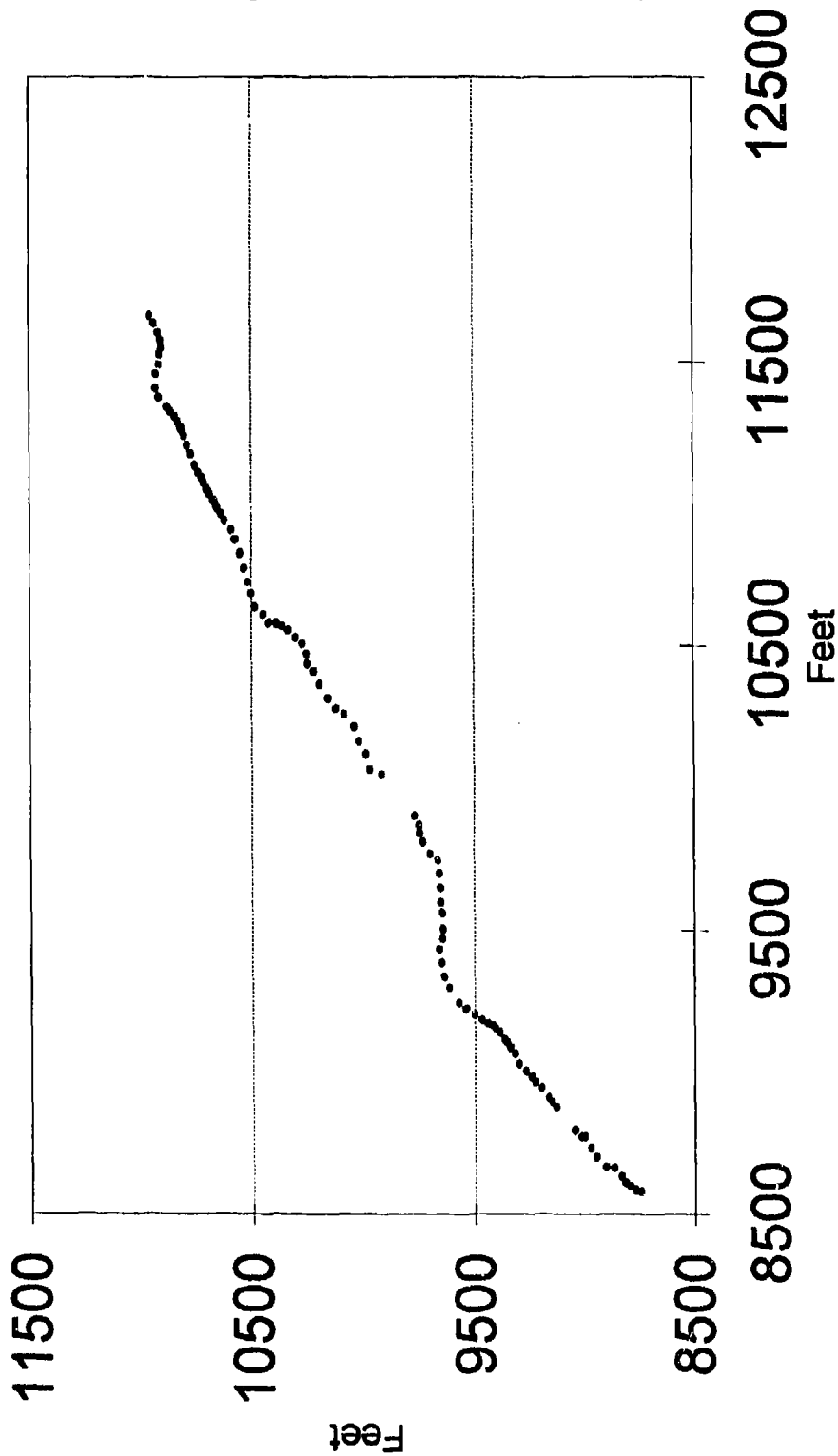


Figure 3.4i Planform of Fannegusha Creek for summer 1994 data.

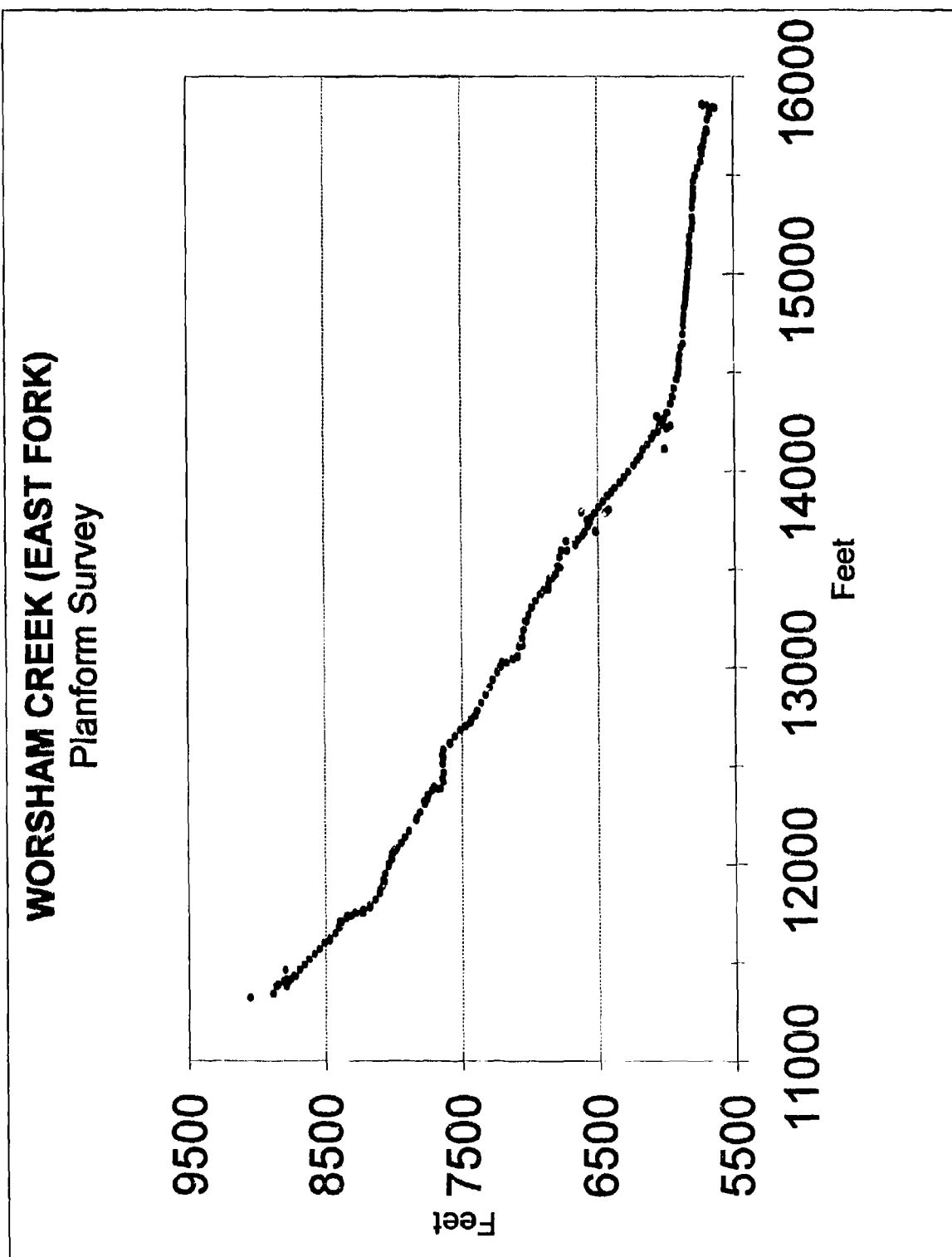


Figure 3.4j Planform of Worsham Creek (East Fork), Site No. 18 for summer 1994 data.

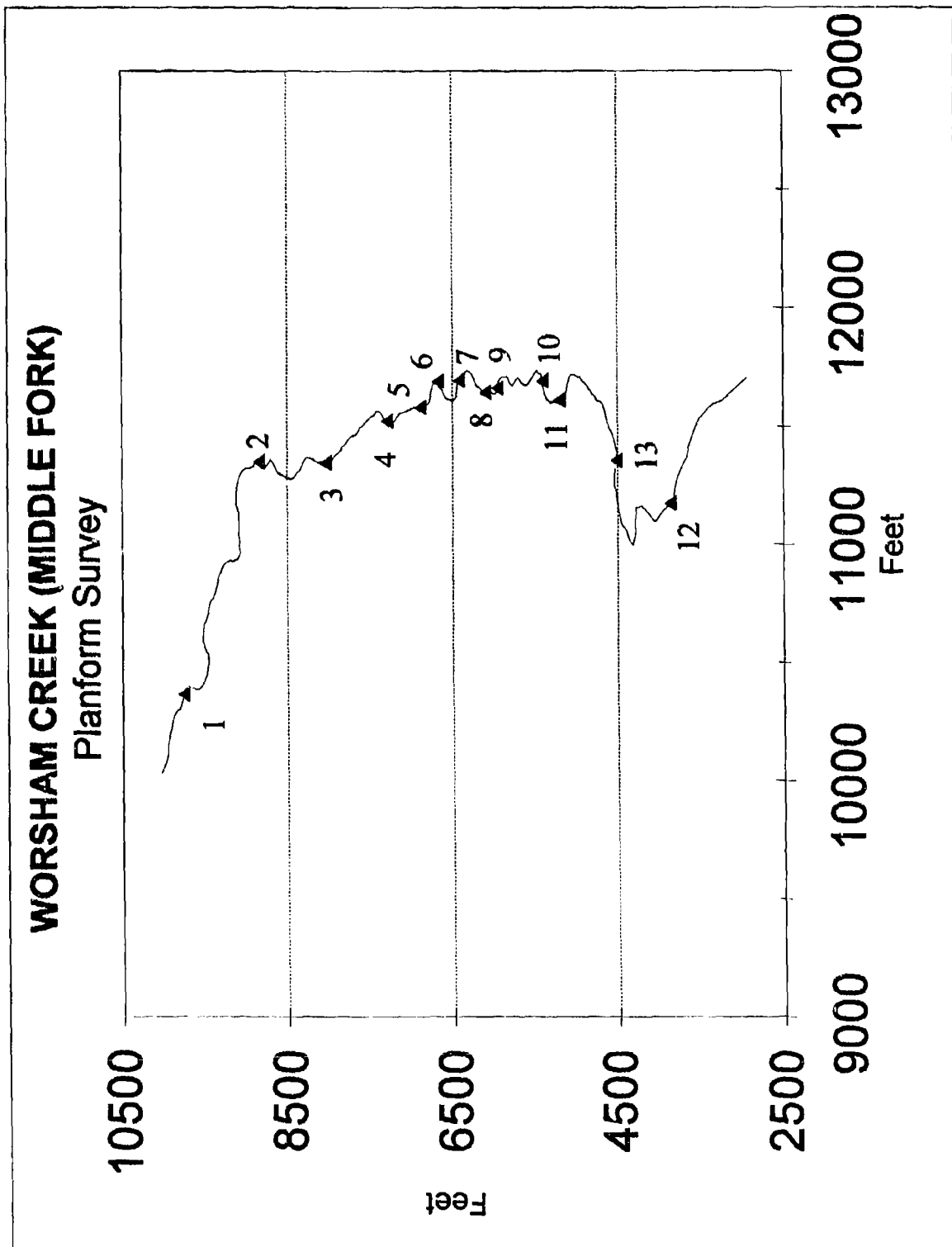


Figure 3.4k, Planform of Worsham Creek (Middle Fork) for summer 1994 data.

WORSHAM CREEK (WEST FORK) Planform Survey

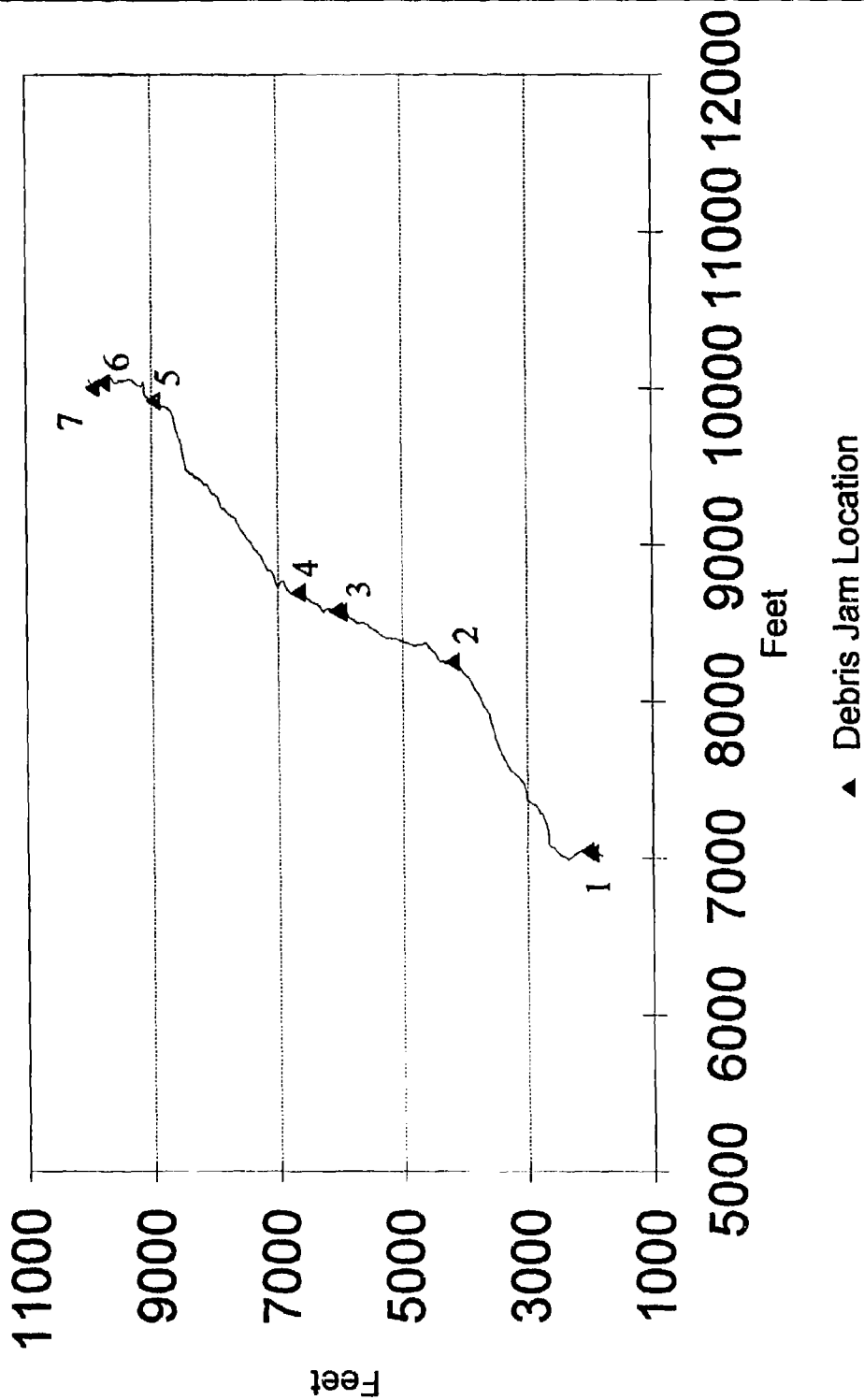


Figure 3.41 Planform of Worsham Creek (West Fork) for summer 1994 data.

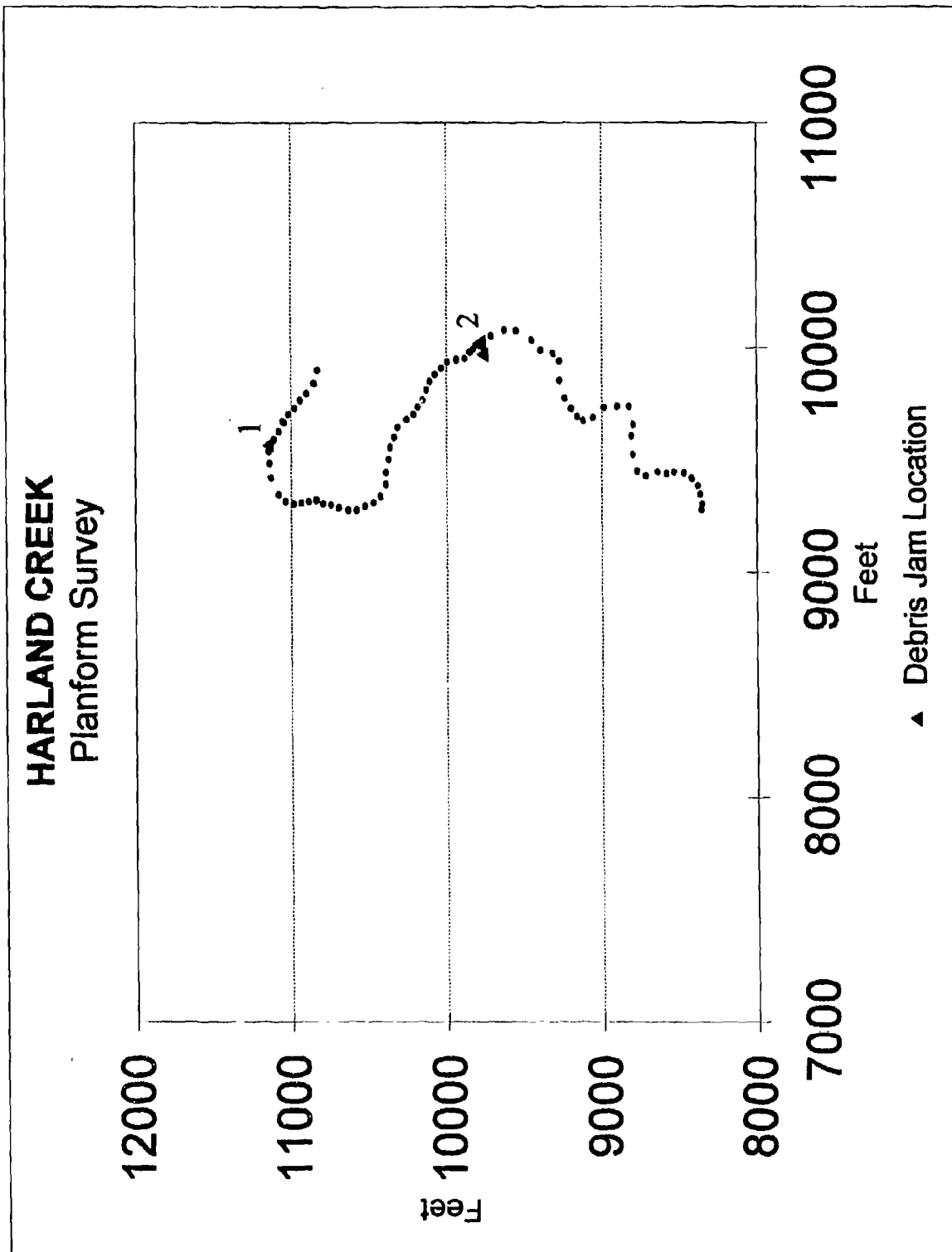


Figure 3.4m Planform of Harland Creek, Site No. 1 for summer 1994 data.

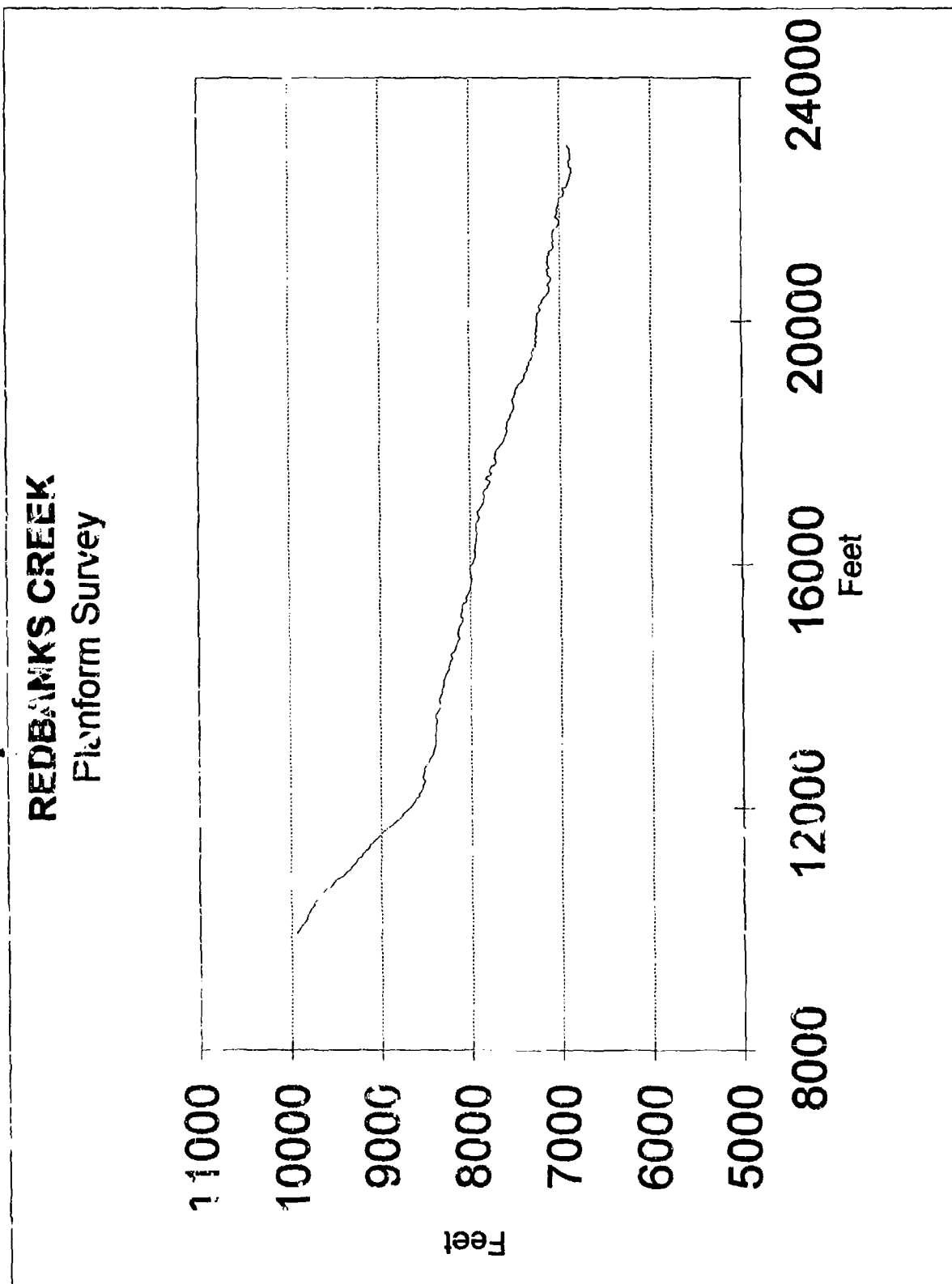


Figure 3.4n Planform of Redbanks Creek for summer 1994 data.

OTOUCALLOFA CREEK Planform Survey

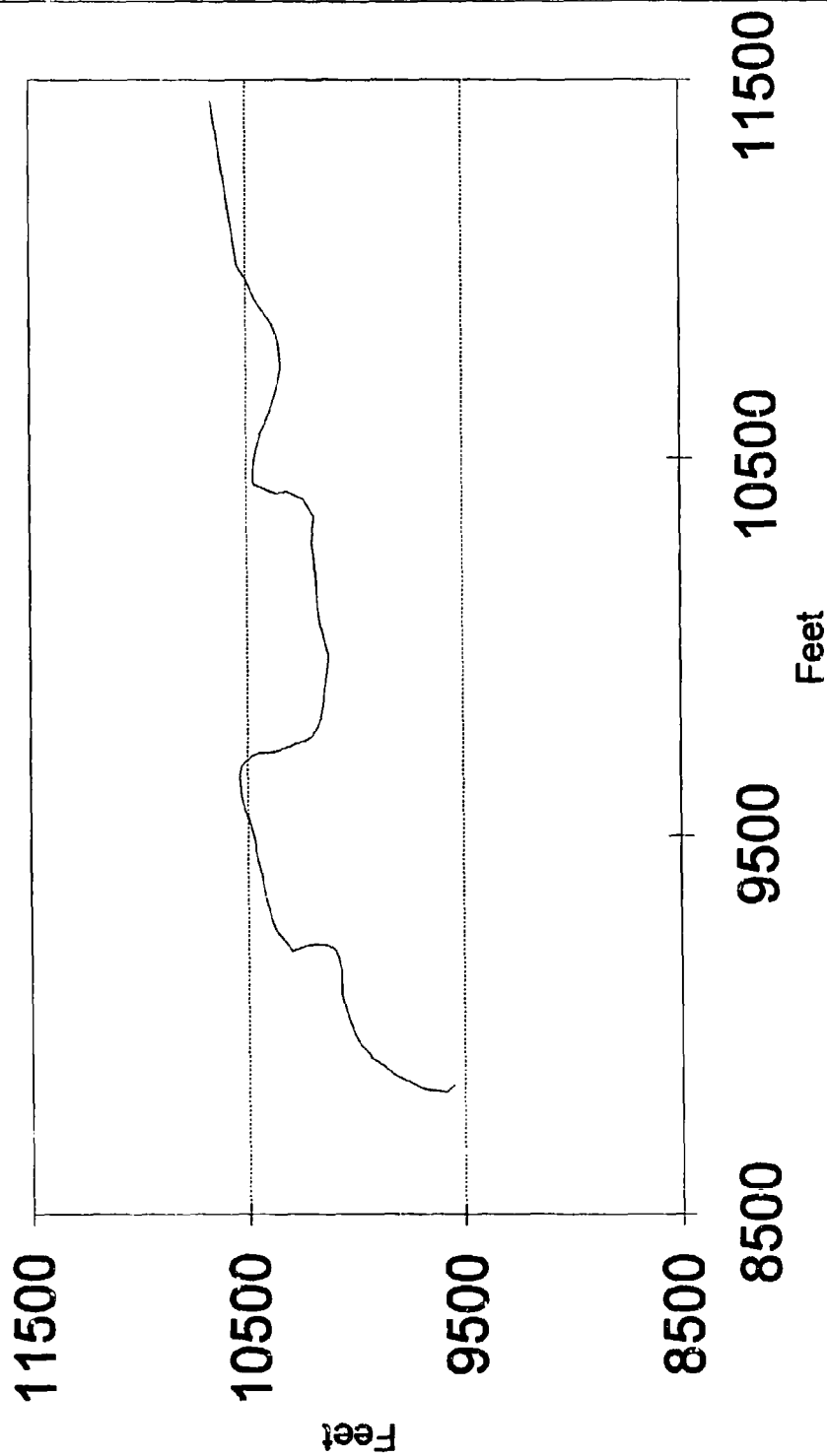


Figure 3.4 of Planform of Otoucallofa Creek for summer 1994 data.

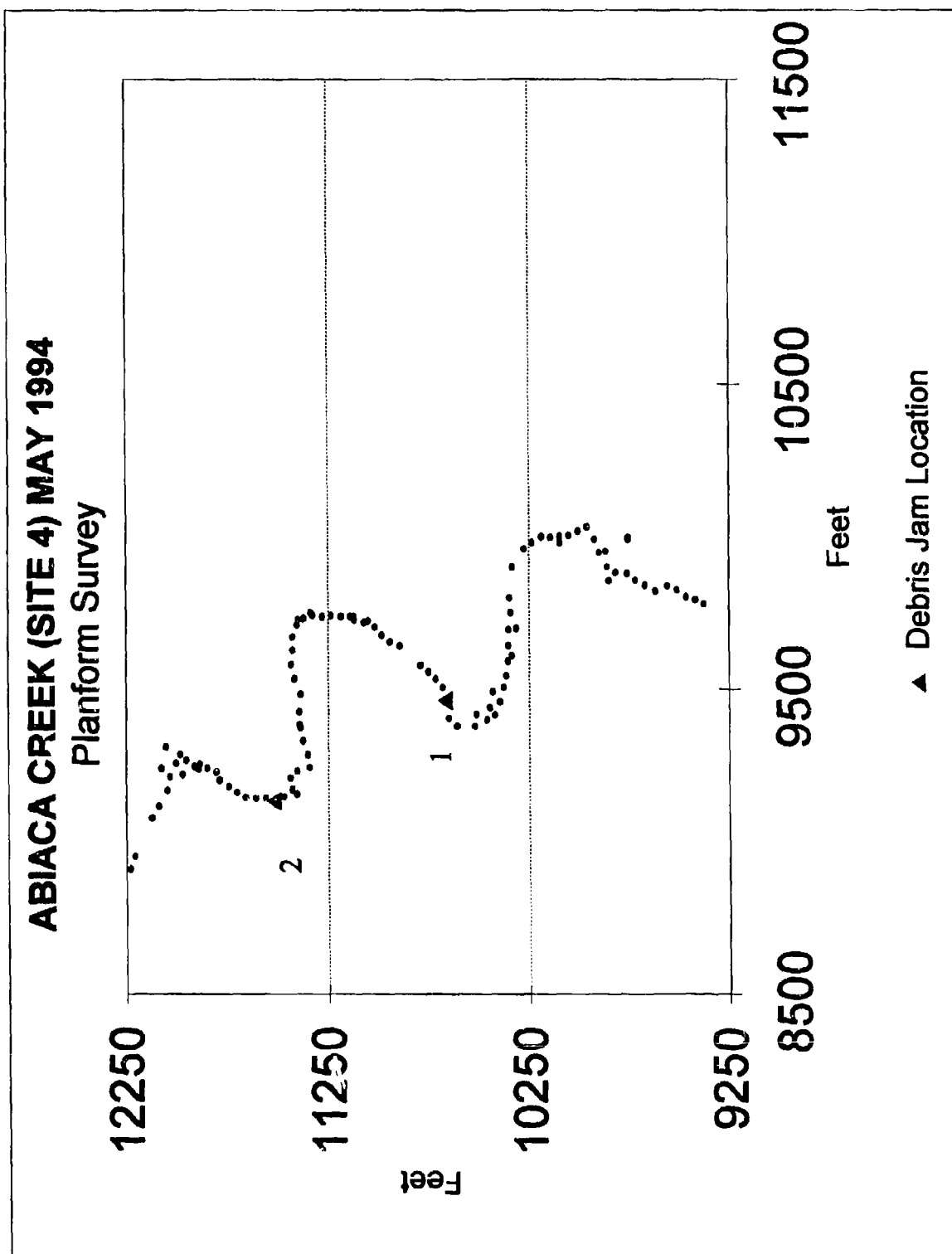


Figure 3.4p Planform of Abiaca Creek, Site No. 4 for summer 1994 data

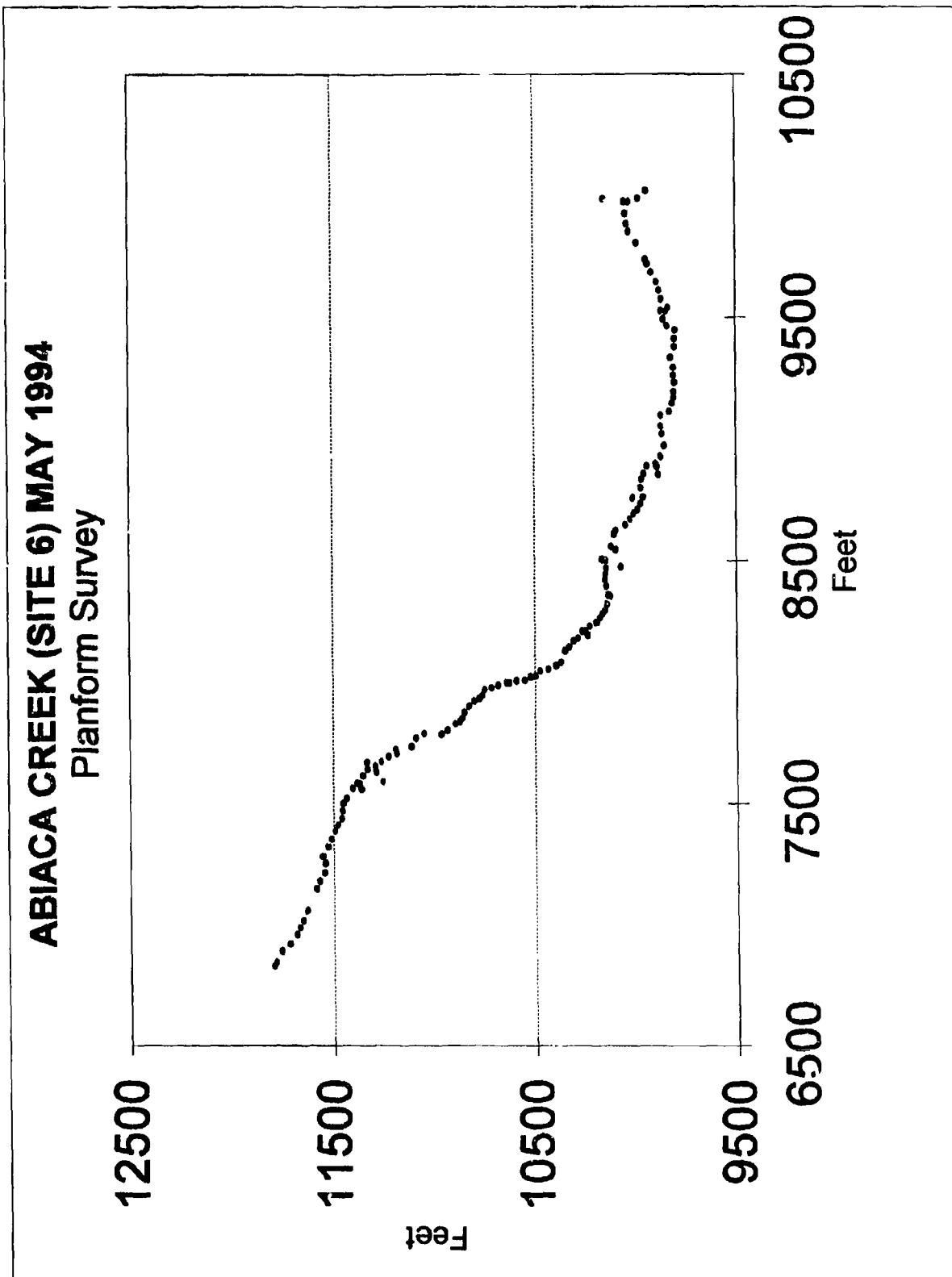


Figure 3.4q Planform of Abiaca Creek, Site No. 6 for summer 1994 data.

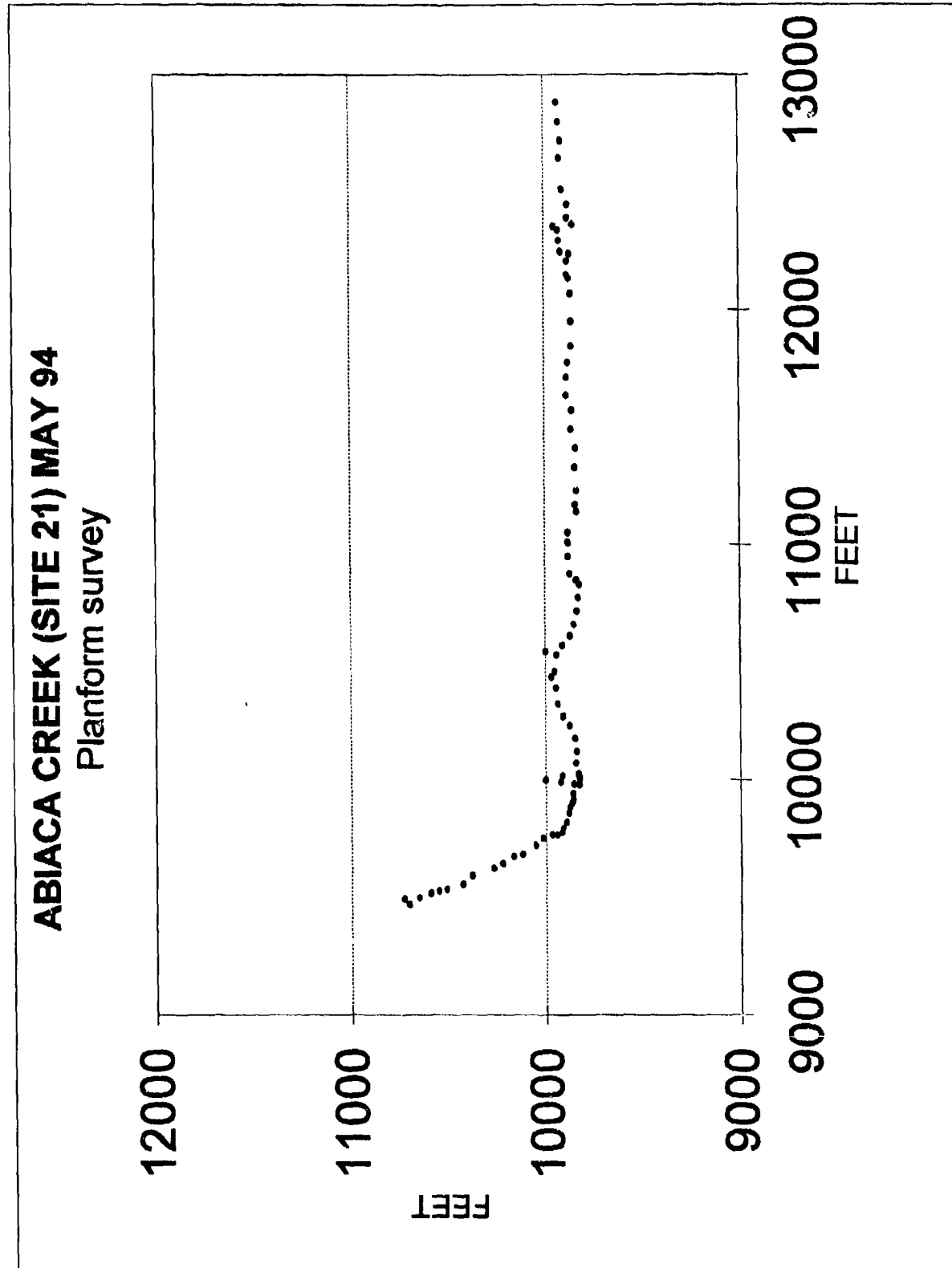


Figure 3.4r Planform of Abiaca Creek, Site 21 for summer 1994 data.

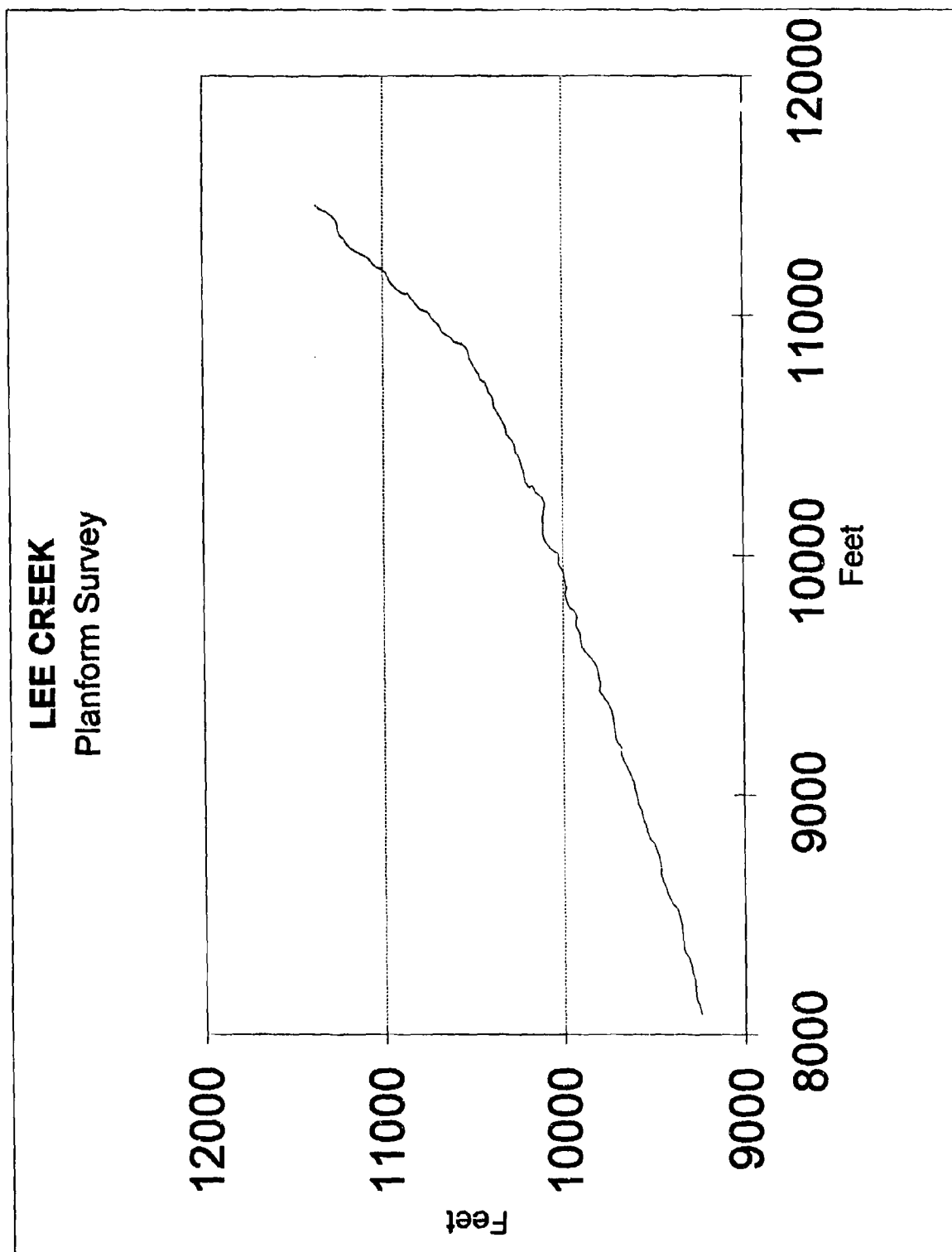


Figure 3.4s Planform of Lee Creek for summer 1994 data.

HICKAHALA CREEK Planform Survey

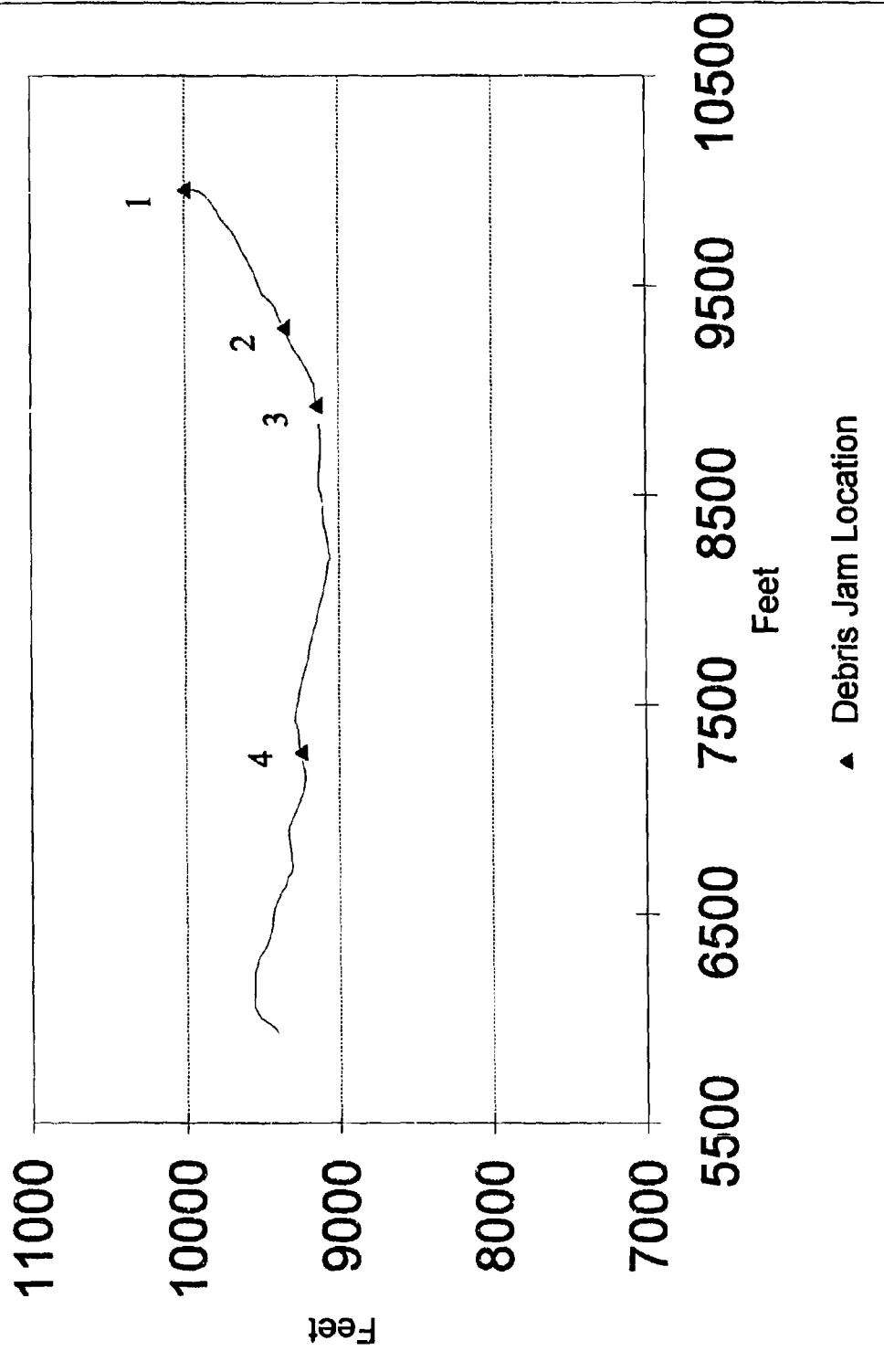


Figure 3.4t Planform of Hickahala Creek for summer 1994 data.

PERRY CREEK
Planform. Survey

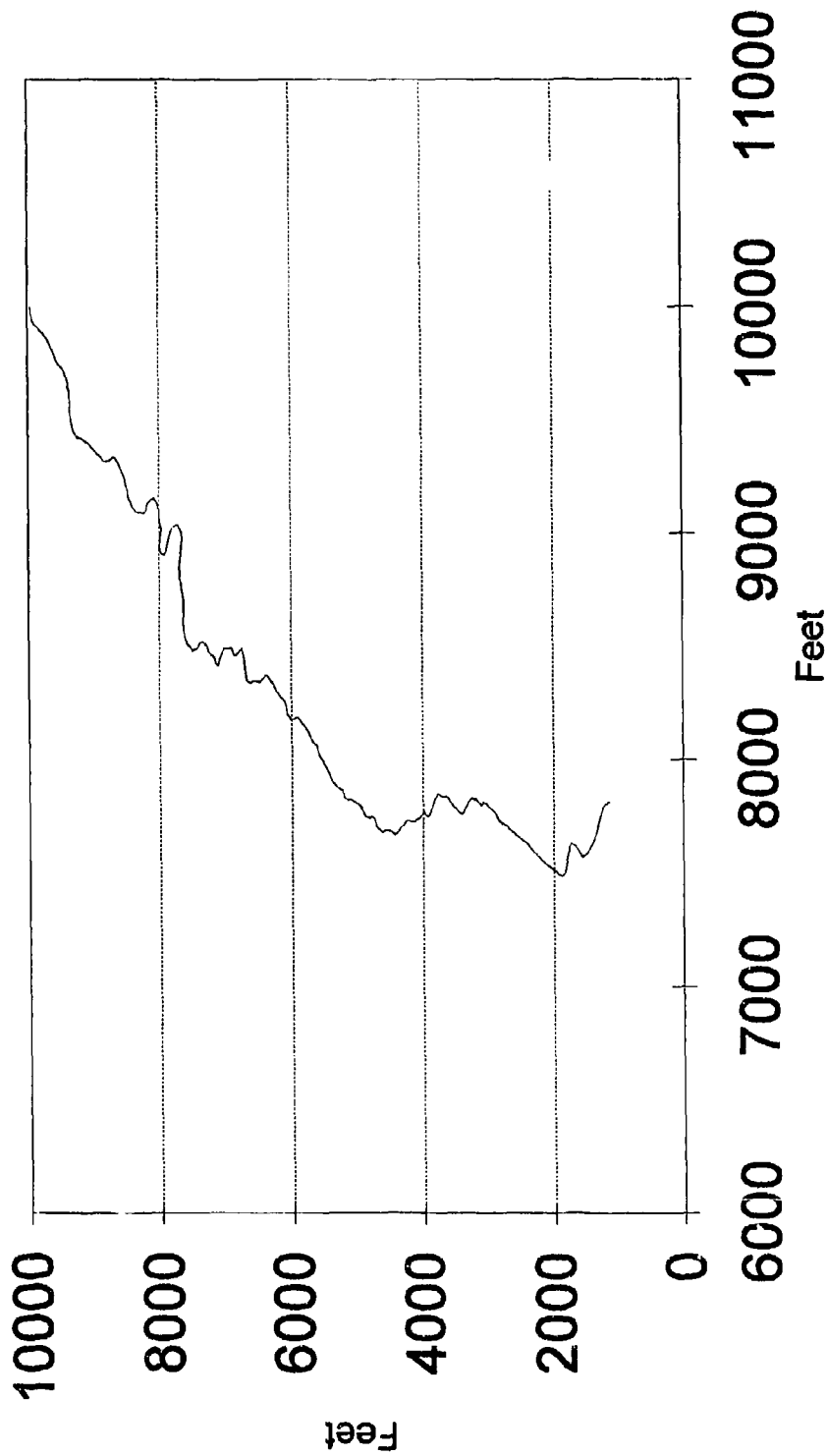


Figure 3.4u Planform of Perry Creek for summer 1994 data.

HARLAND CREEK (SITE 23) Planform Survey

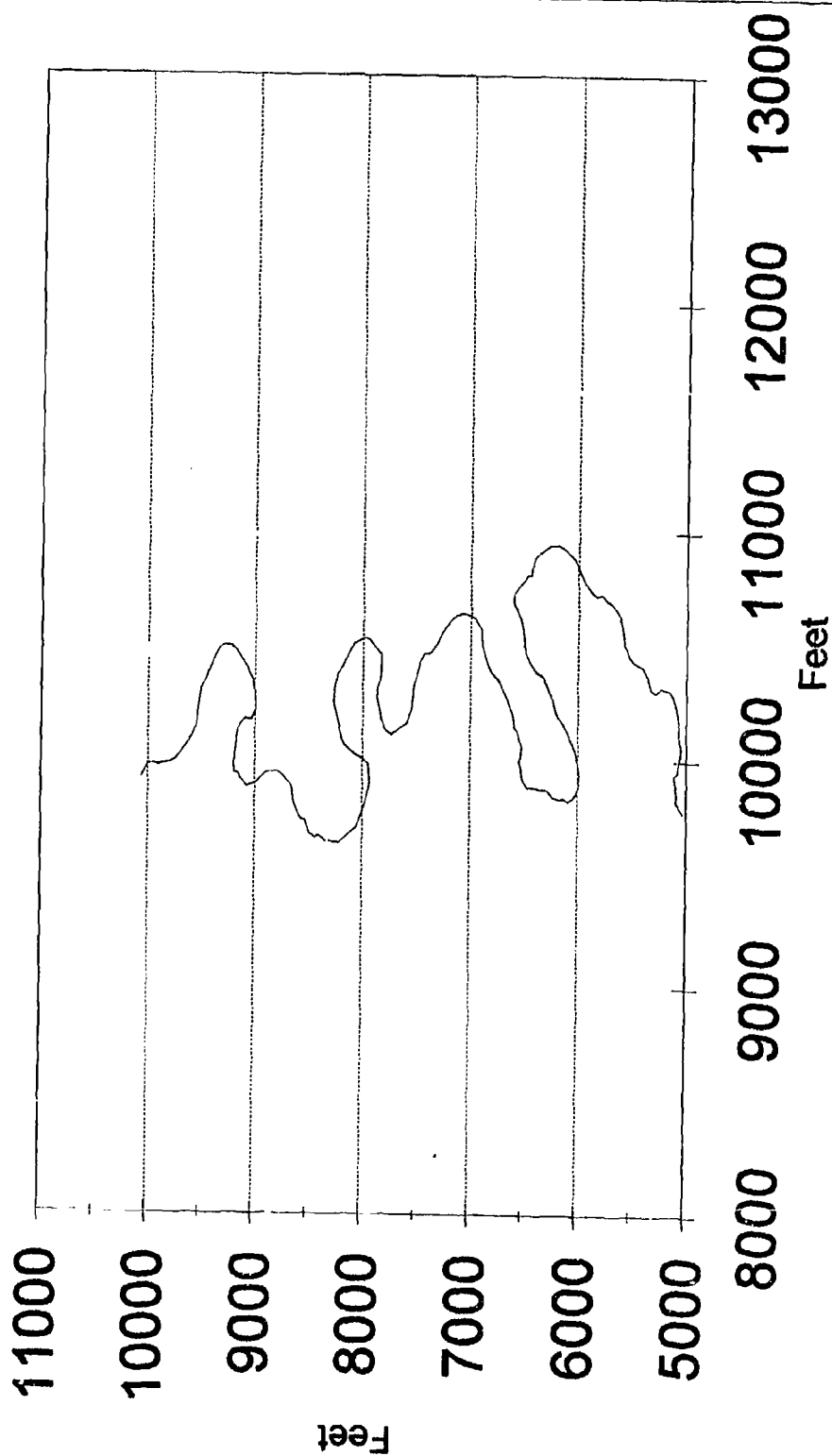


Figure 3.4v Planform of Harland Creek, Site No. 23 for summer 1994 data.

NOLEHOE CREEK Thalweg Survey Profile

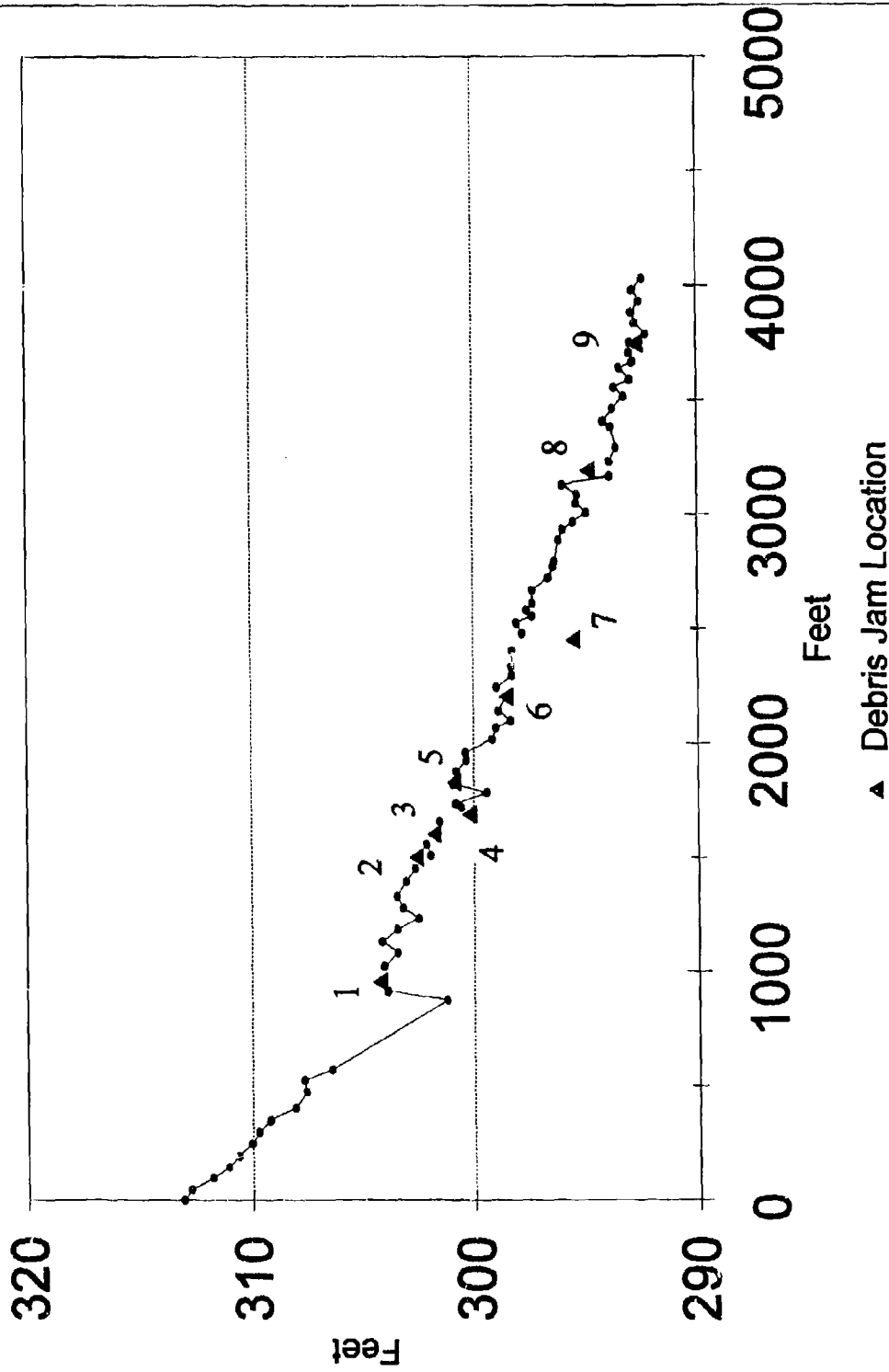


Figure 3.5a Thalweg Profile of Nolehoe Creek for summer 1994 data.

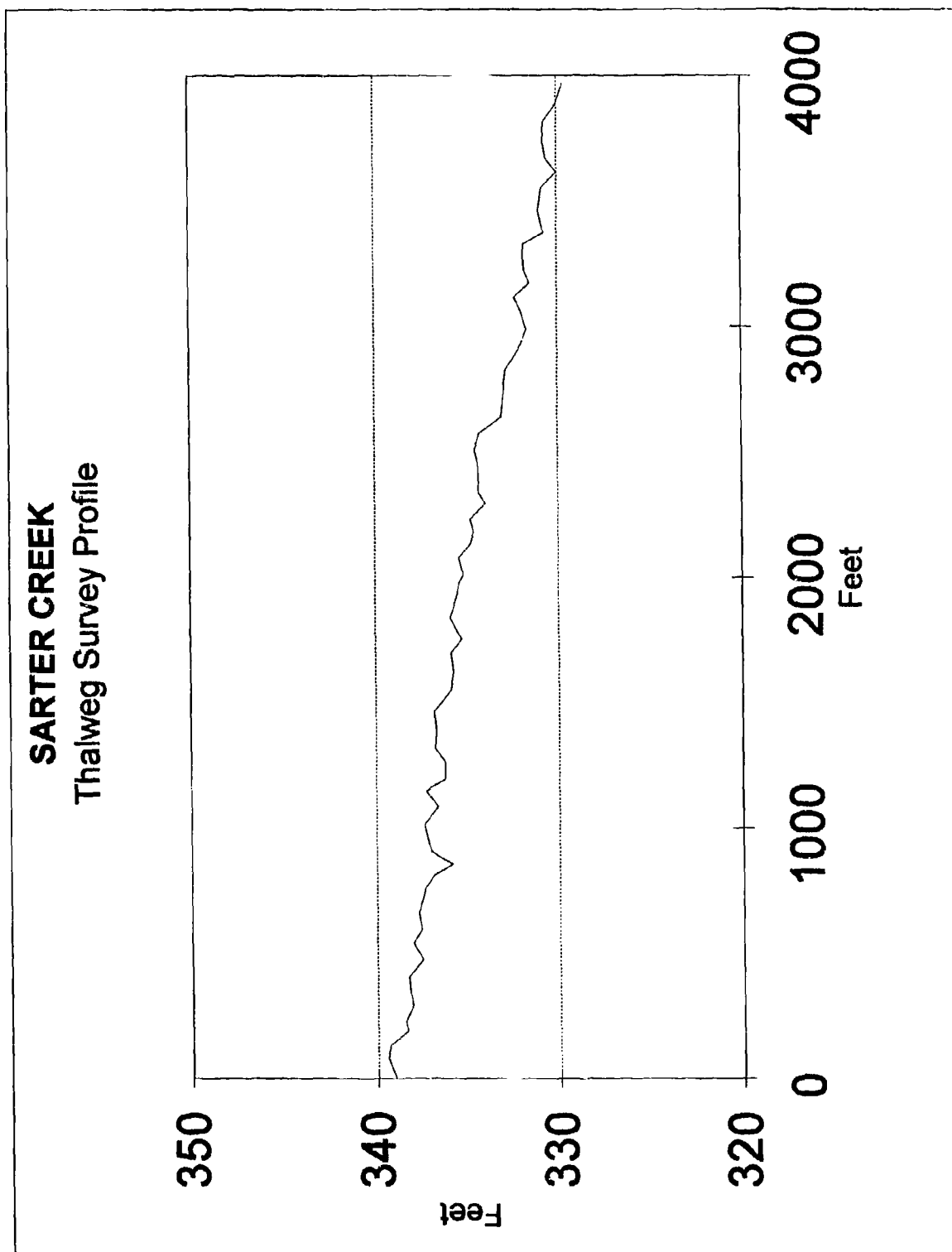


Figure 3.5b Thalweg Profile of Sarter Creek for summer 1994 data.

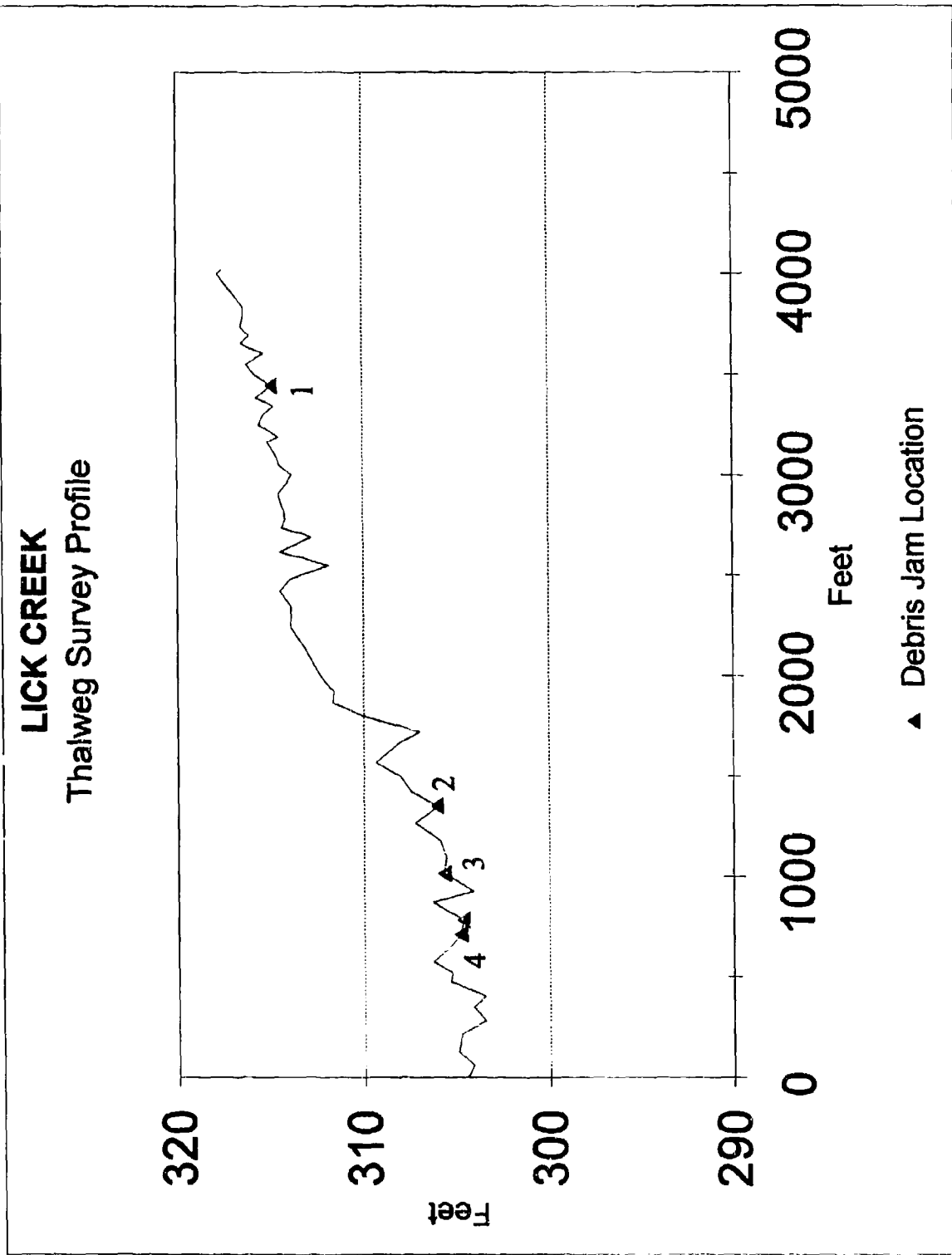


Figure 3.5c Thalweg Profile of Lick Creek for summer 1994 data.

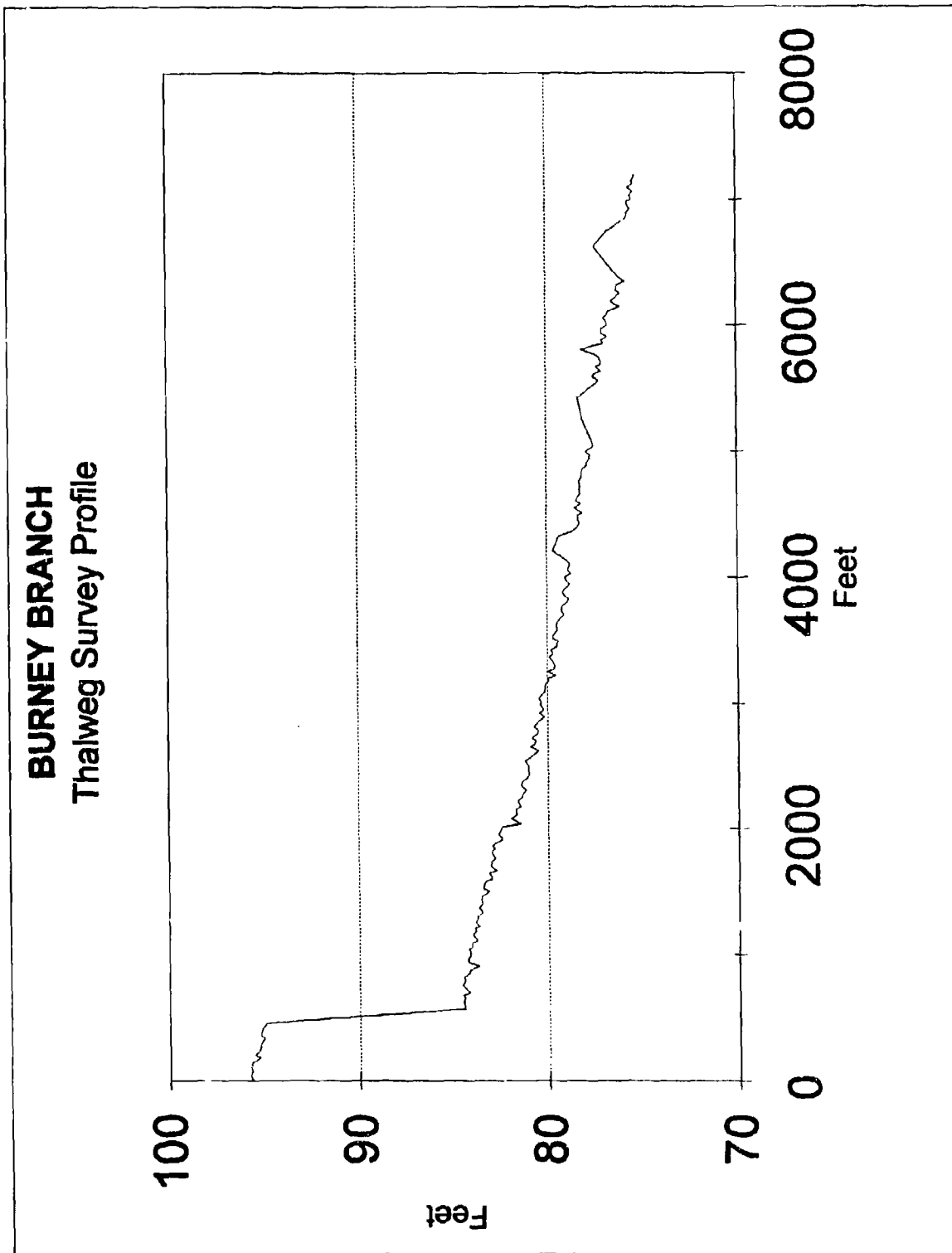


Figure 3.5d Thalweg Profile of Burney Branch for summer 1984 data.

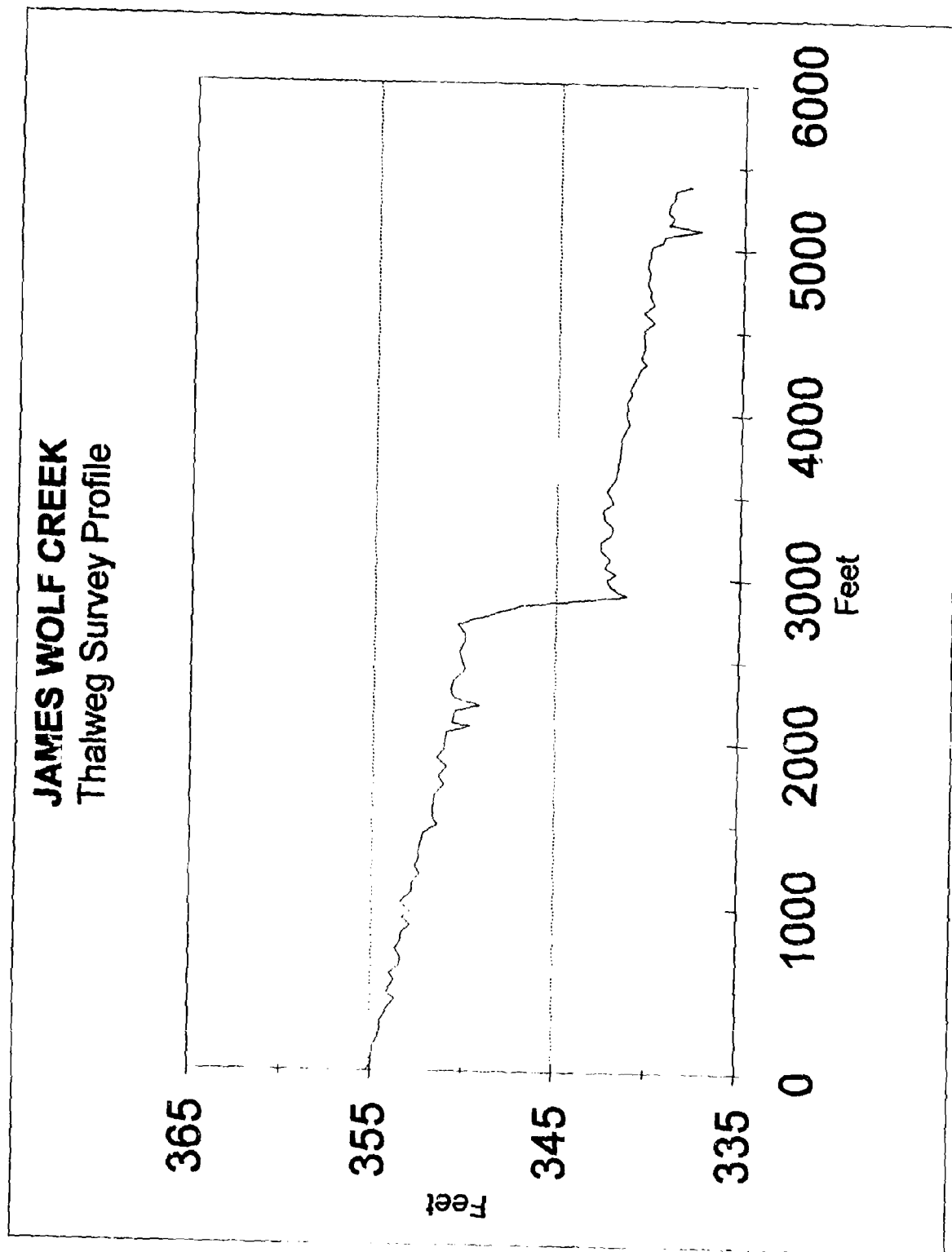


Figure 3.5e Thalweg Profile of James Wolf Creek for summer 1994 data.

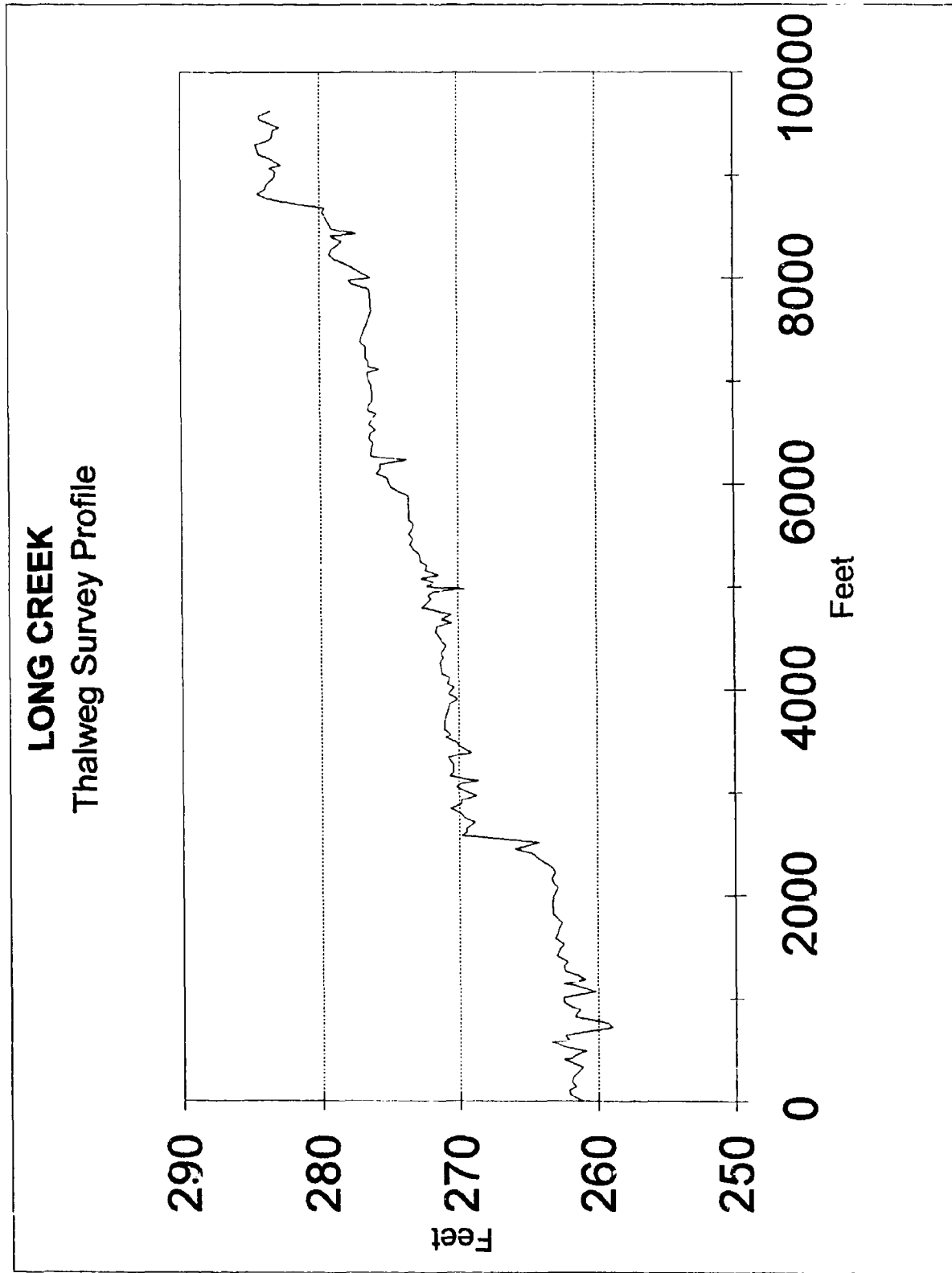


Figure 3.5f Thalweg Profile of Long Creek for summer 1994 data.

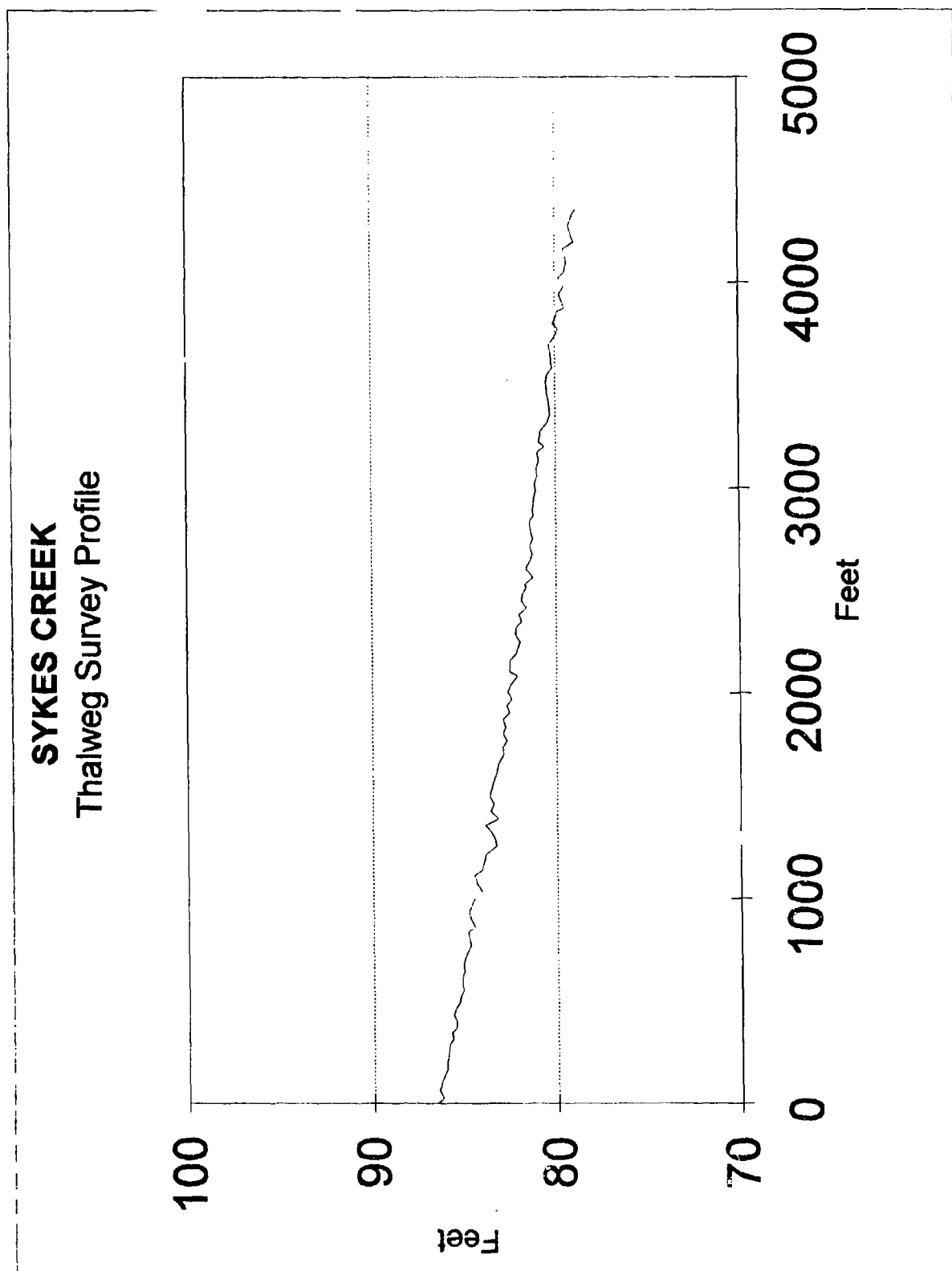


Figure 3.5g Thalweg Profile of Sykes Creek for summer 1994 data.

HOTOPHA CREEK Thalweg Survey Profile

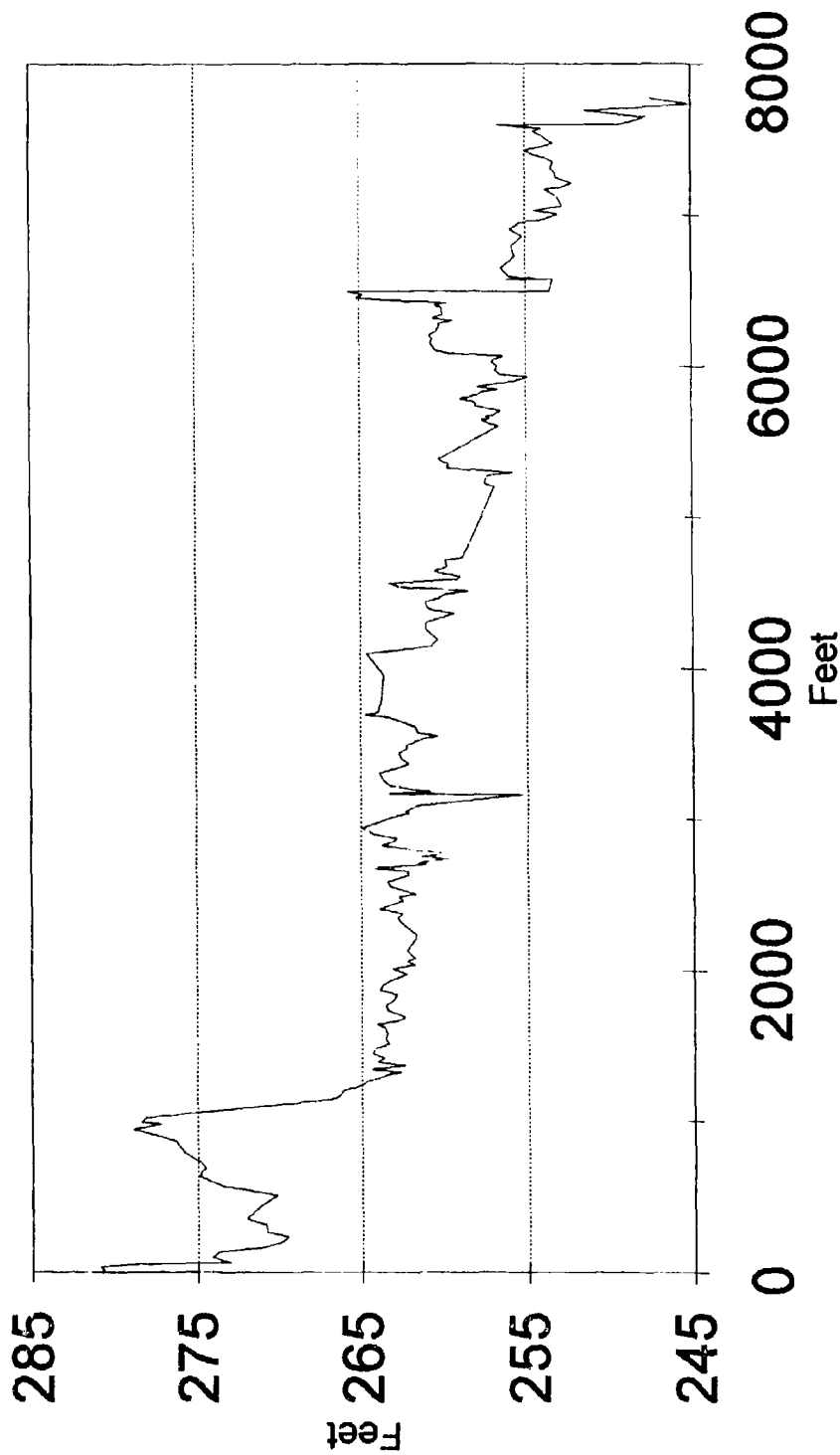


Figure 3.5h Thalweg Profile of Hotopha Creek for summer 1994 data.

FANNEGUSHA CREEK **Thalweg Survey Profile**

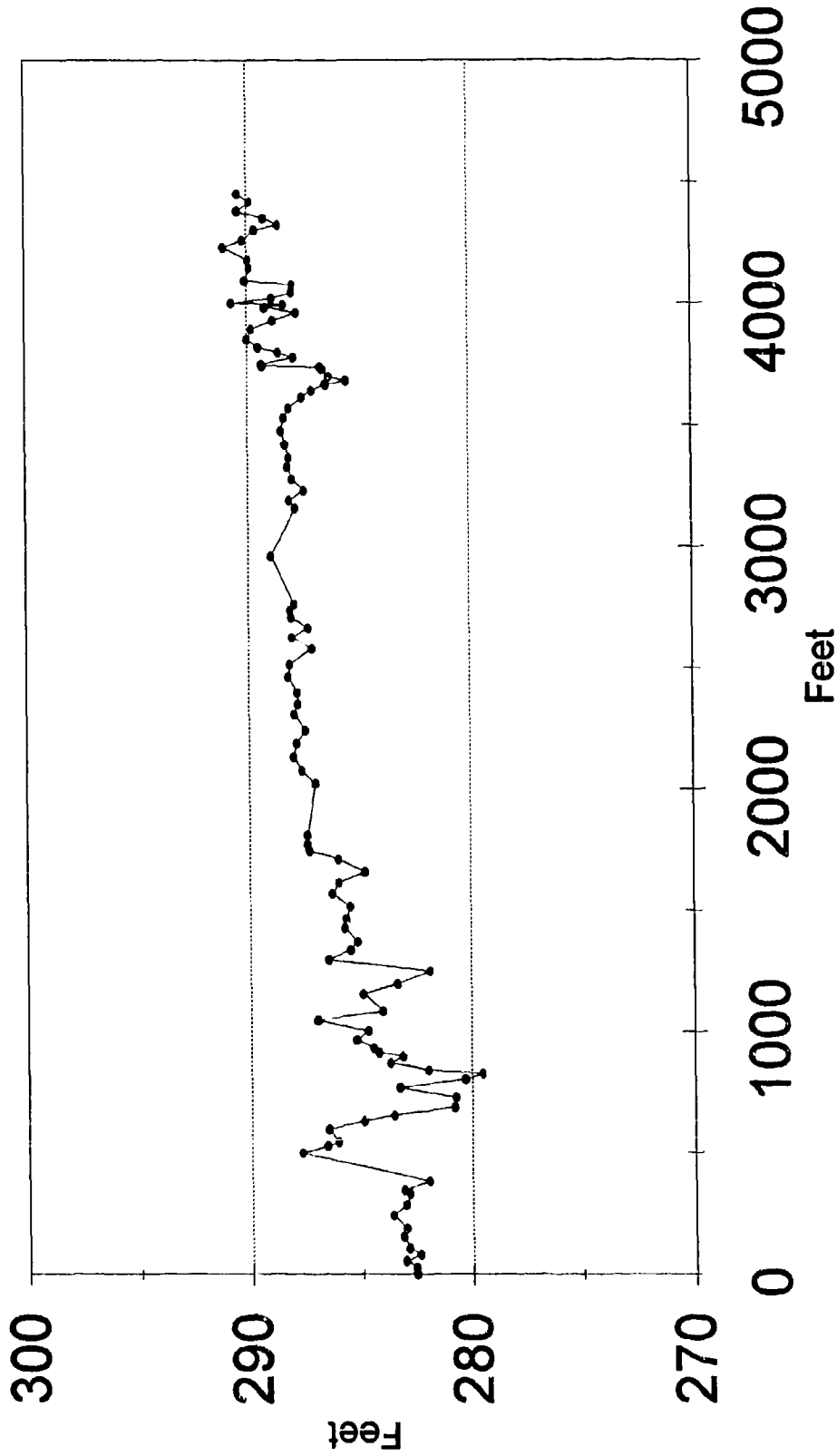


Figure 3.5j Thalweg Profile of Fannegusha Creek for summer 1994 data.

WORSHAM CREEK (EAST FORK)
Thalweg Survey Profile

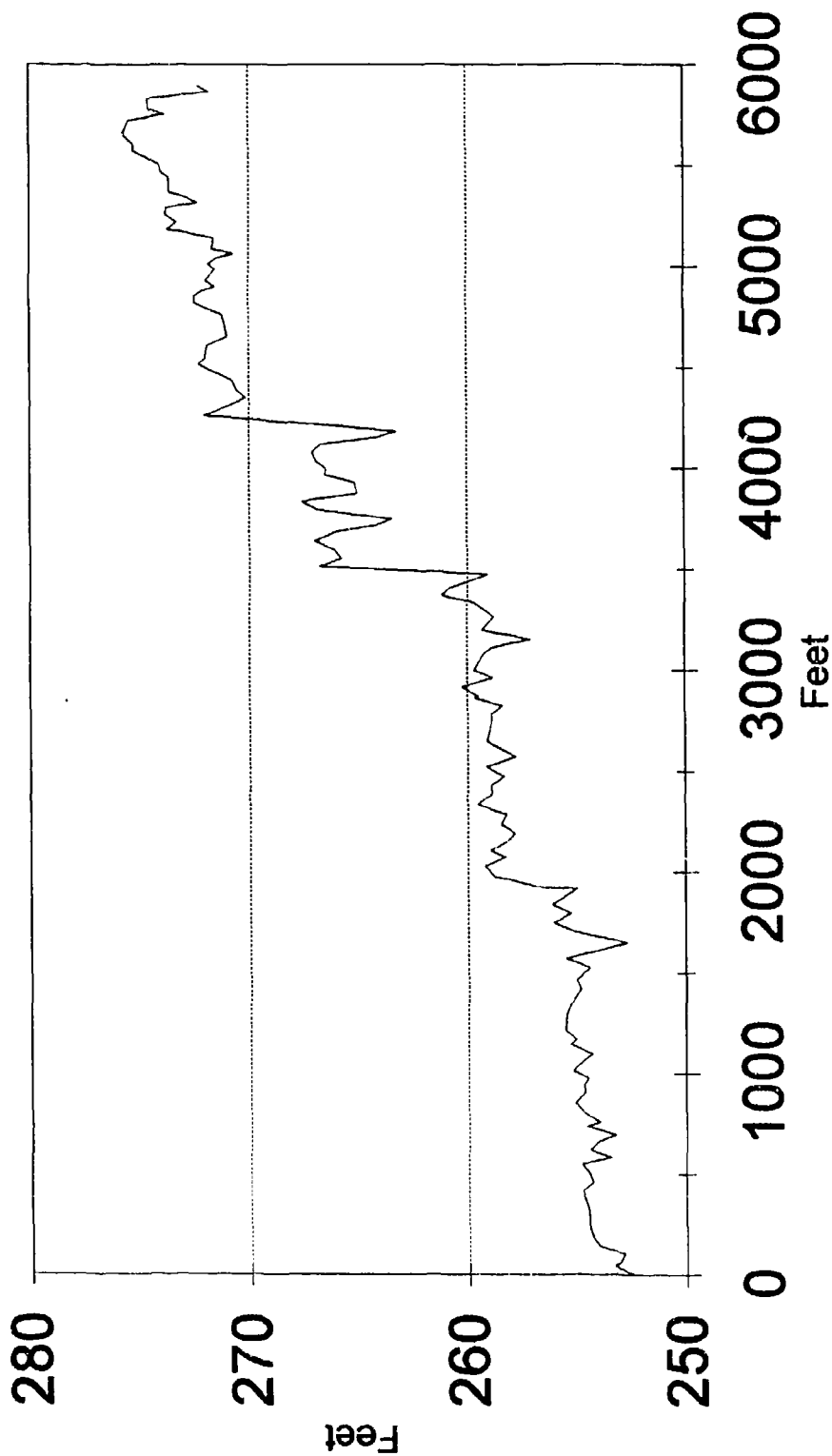


Figure3.5j Thalweg Profile of Worsham Creek (East Fork), Site No. 18 for summer 1994 data.

WORSHAM CREEK (MIDDLE FORK) **Thalweg Survey Profile**

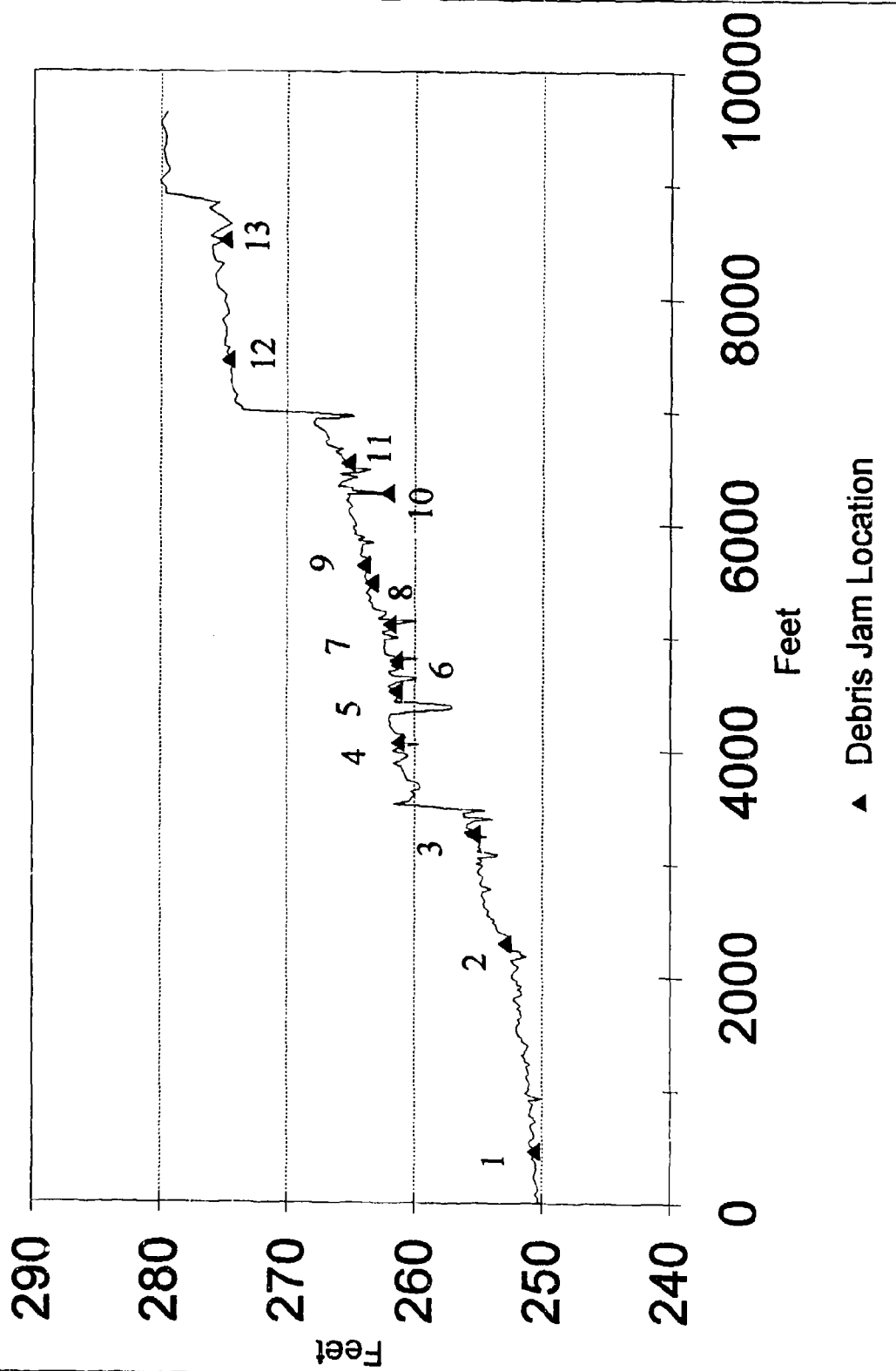


Figure 3.5k Thalweg Profile of Worsham Creek (Middle Fork) for summer 1994 data.

WORSHAM CREEK (WEST FORK) Thalweg Survey Profile

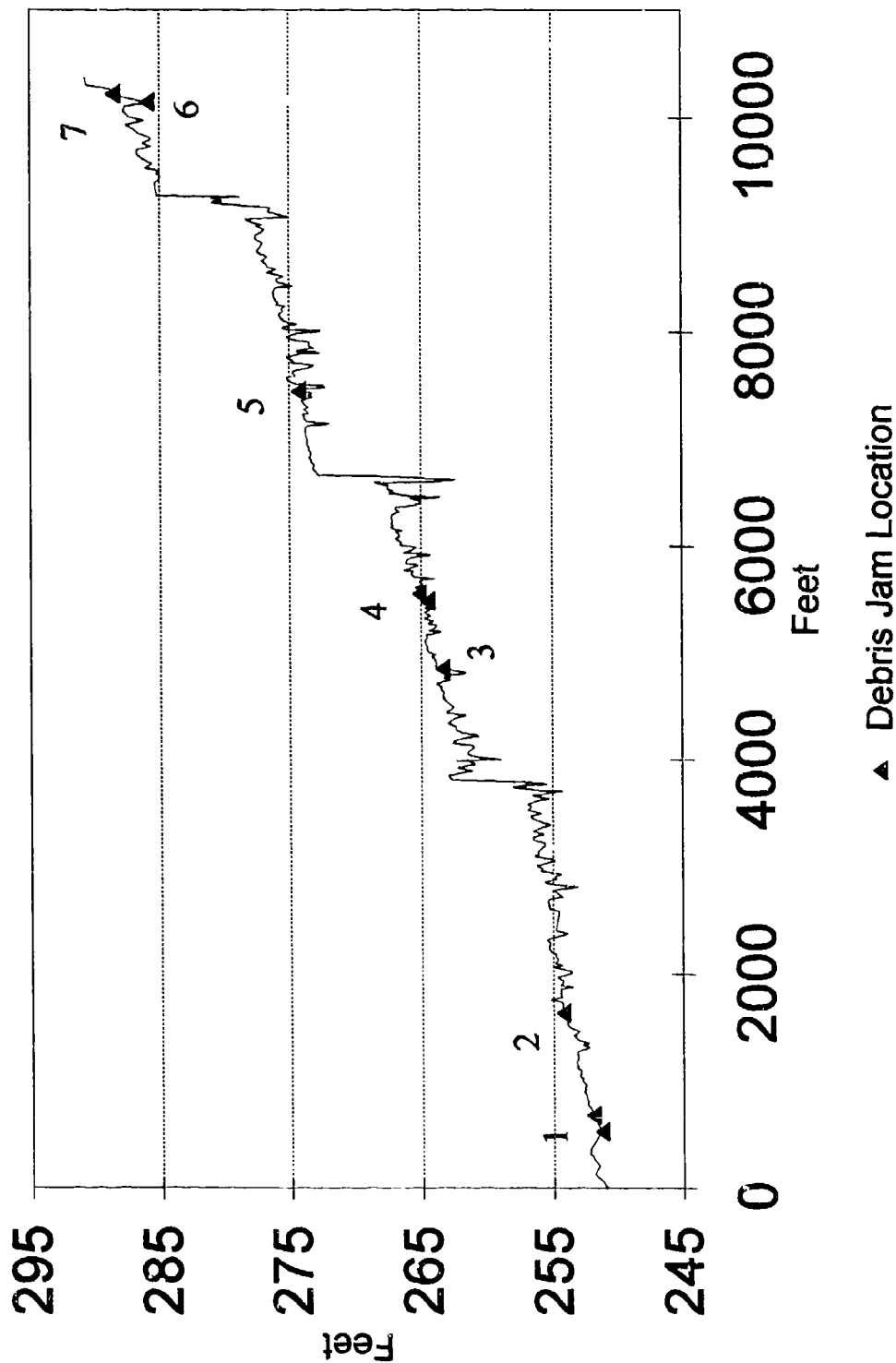


Figure 3.5| Thalweg Survey of Worsham Creek (West Fork) for summer 1994 data.

HARLAND CREEK Thalweg Survey Profile

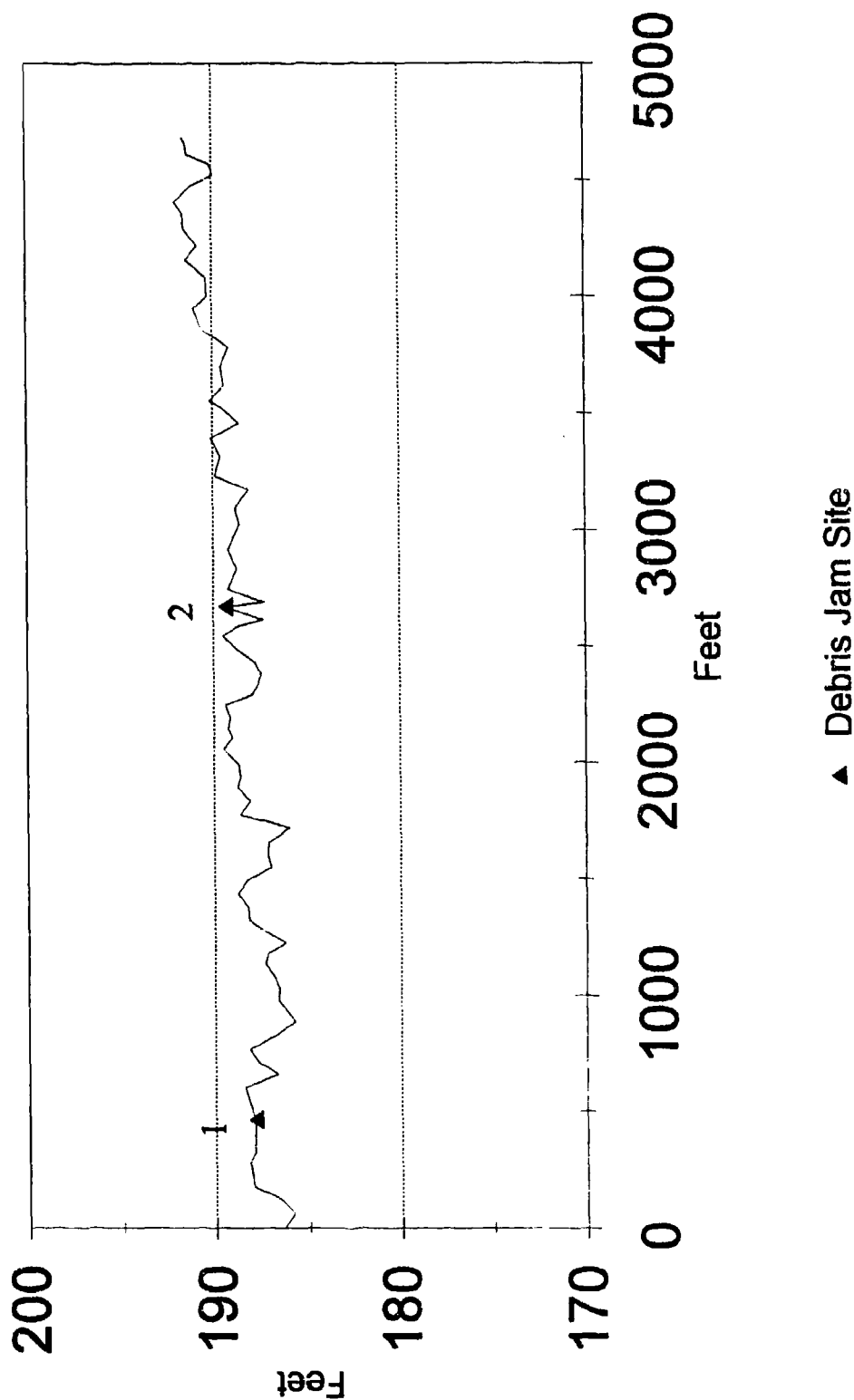


Figure 3.5m Thalweg Profile of Harland Creek, Site No. 1 for summer 1994 data.

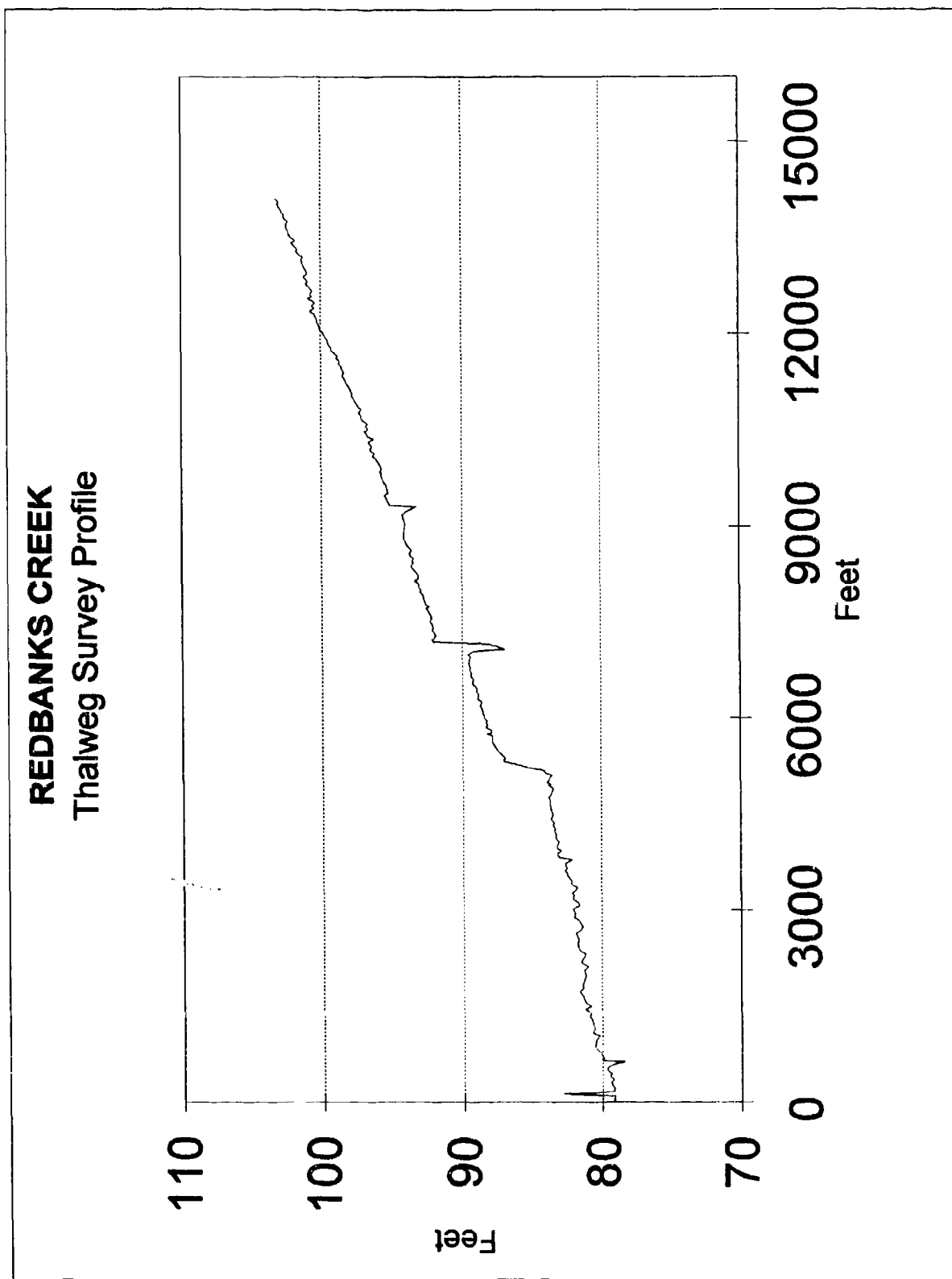


Figure 3.5n Thalweg Profile of Redbanks Creek for summer 1994 data.

OTOUCALLOFA CREEK Thalweg Survey Profile

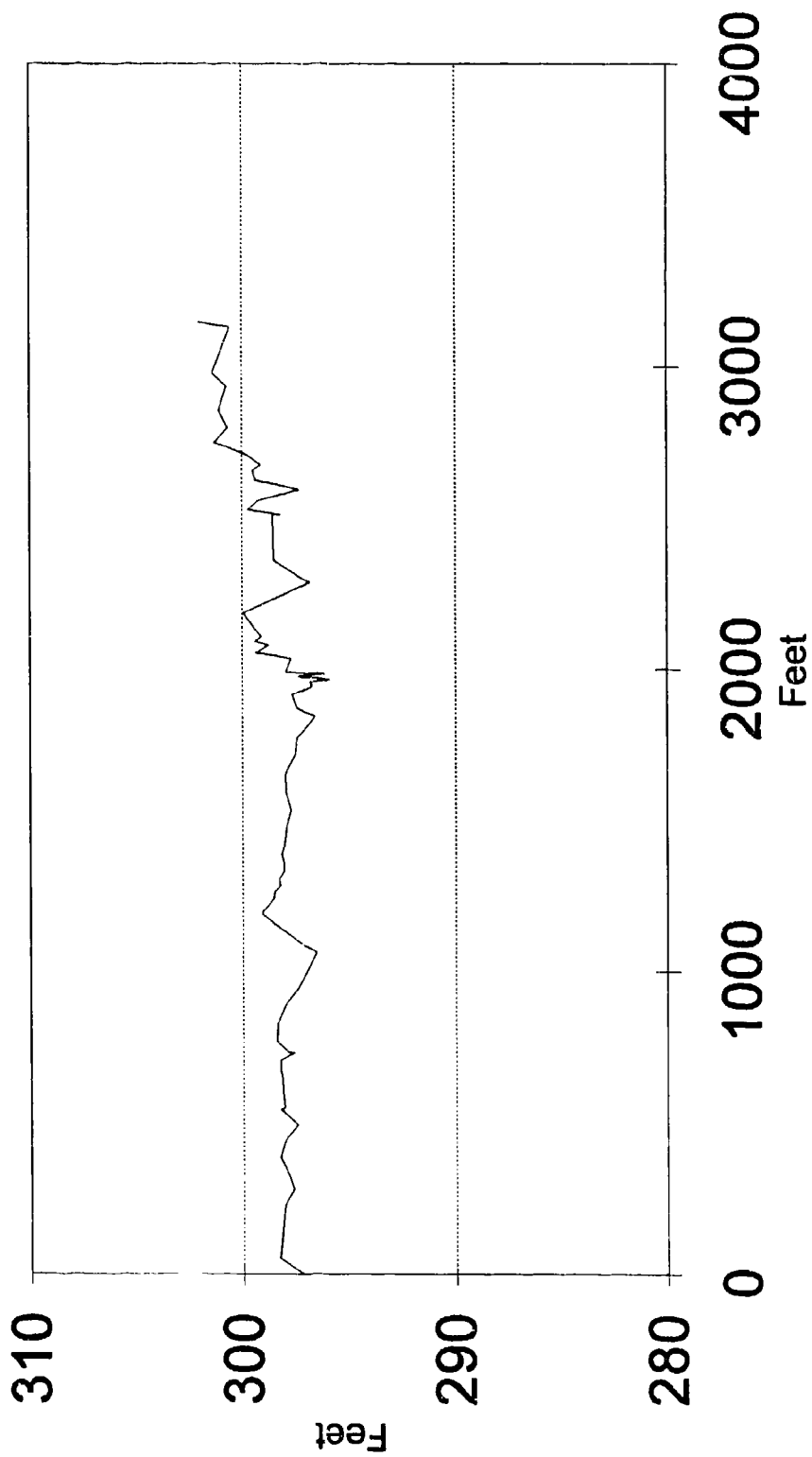


Figure 3.5 Thalweg Profile of OTOUCALLOFA CREEK for summer 1994 data.

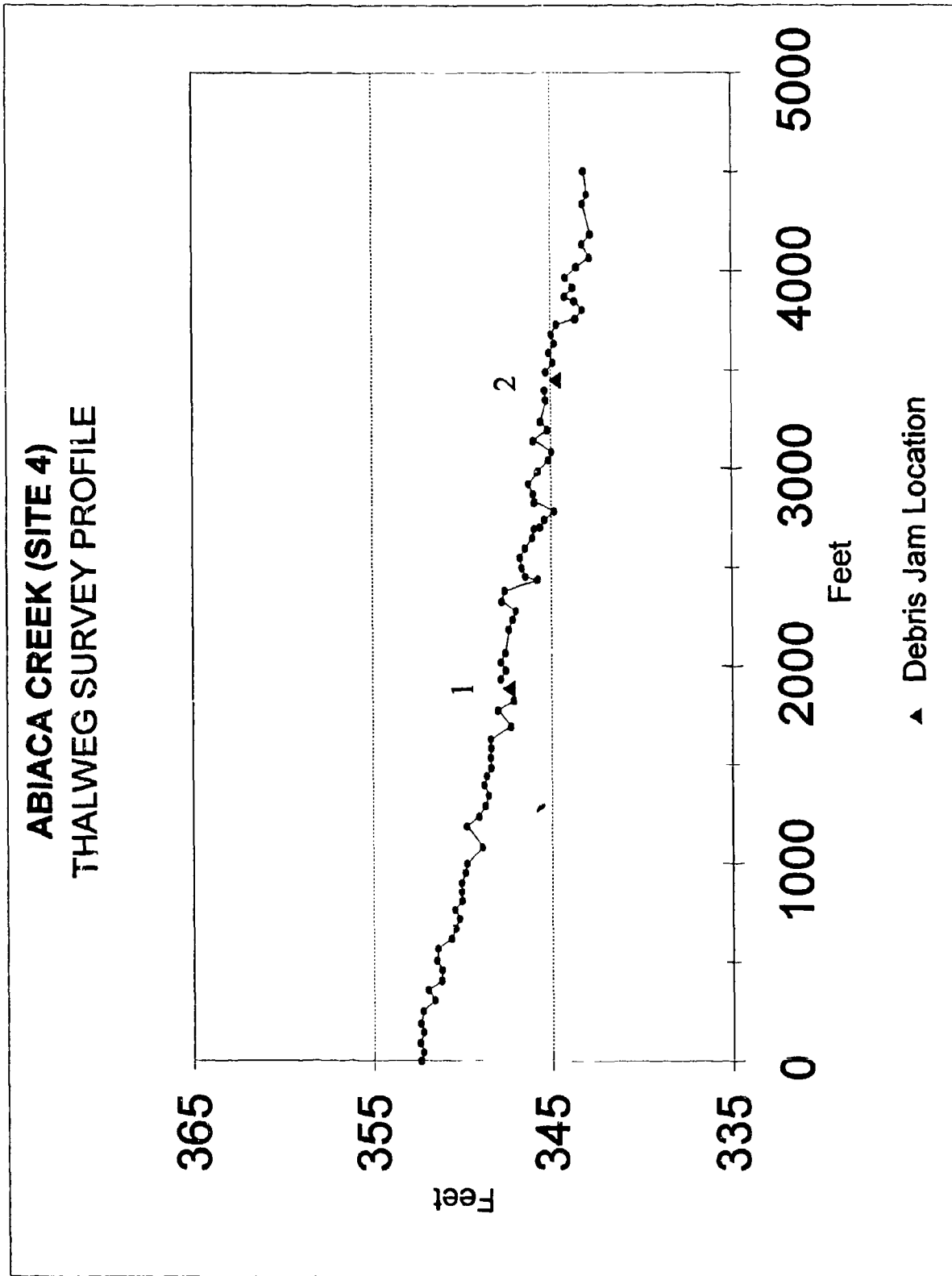


Figure 3.5p Thalweg Profile of Abiaca Creek, Site No. 4 for summer 1994 data

ABIACA CREEK (SITE 6)
Thalweg Survey Profile

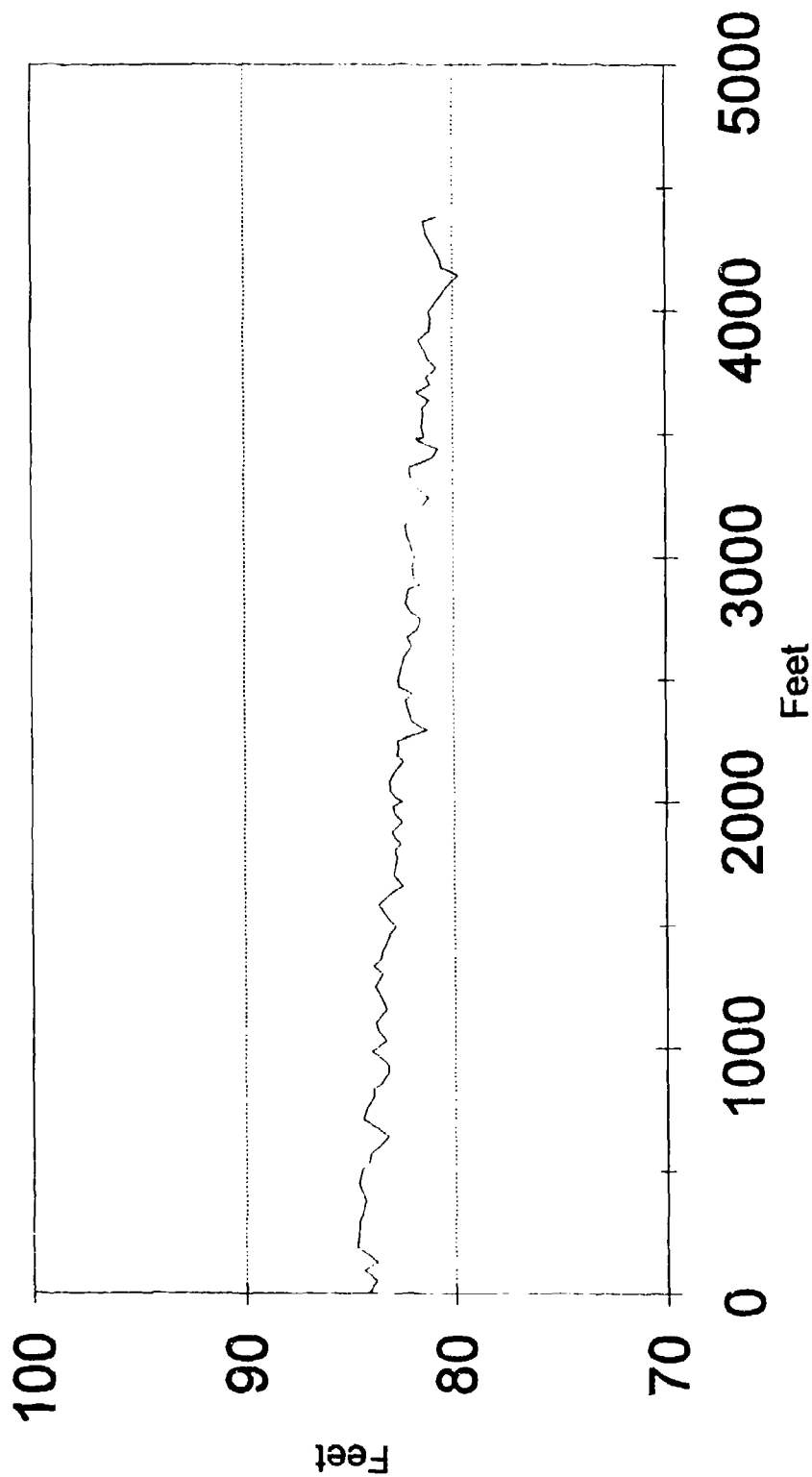


Figure 3.5q Thalweg Profile of Abiaca Creek, Site No. 6 for summer 1994 data.

ABIACA CREEK (SITE 21) MAY 94
Thalweg Survey Profile

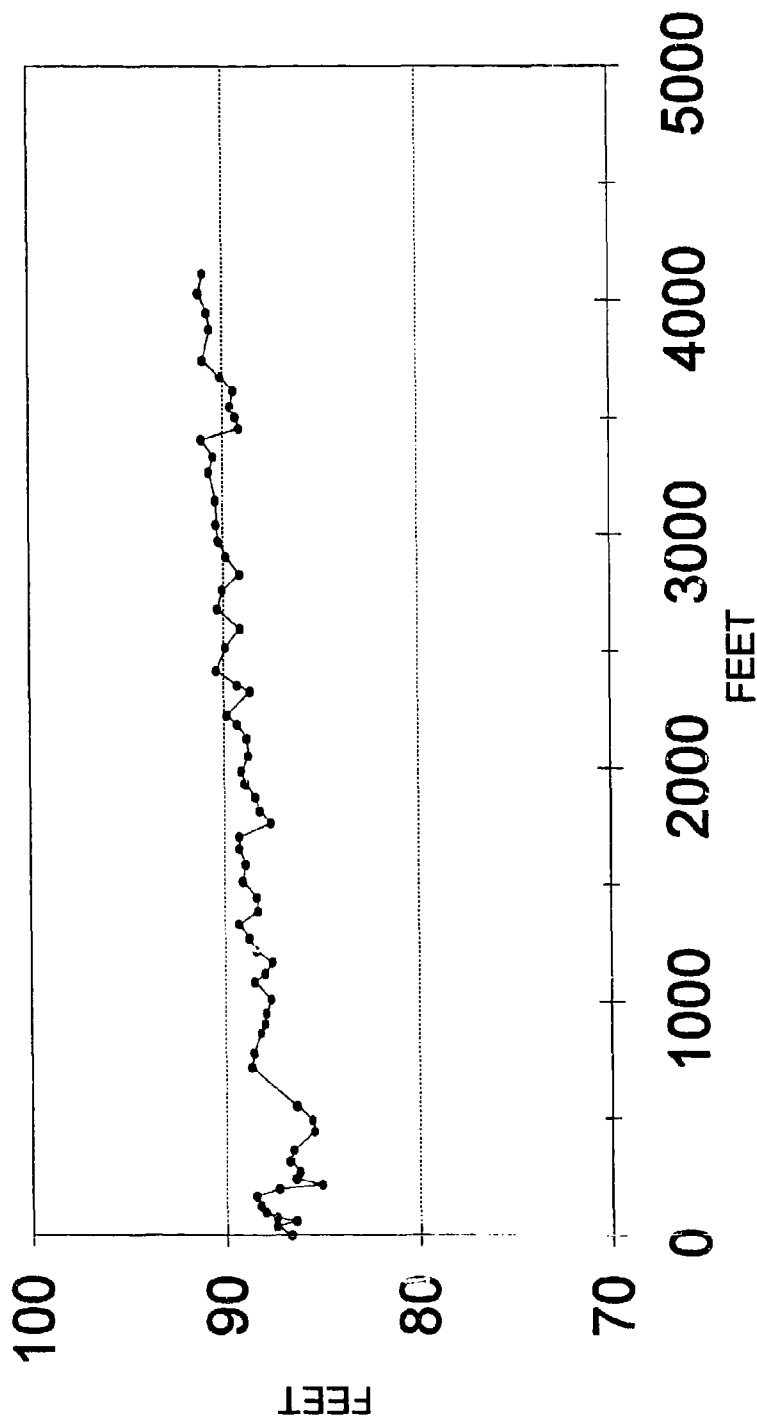


Figure 3.5r Thalweg Profile of Abiaca Creek, Site No. 21 for summer 1994 data.

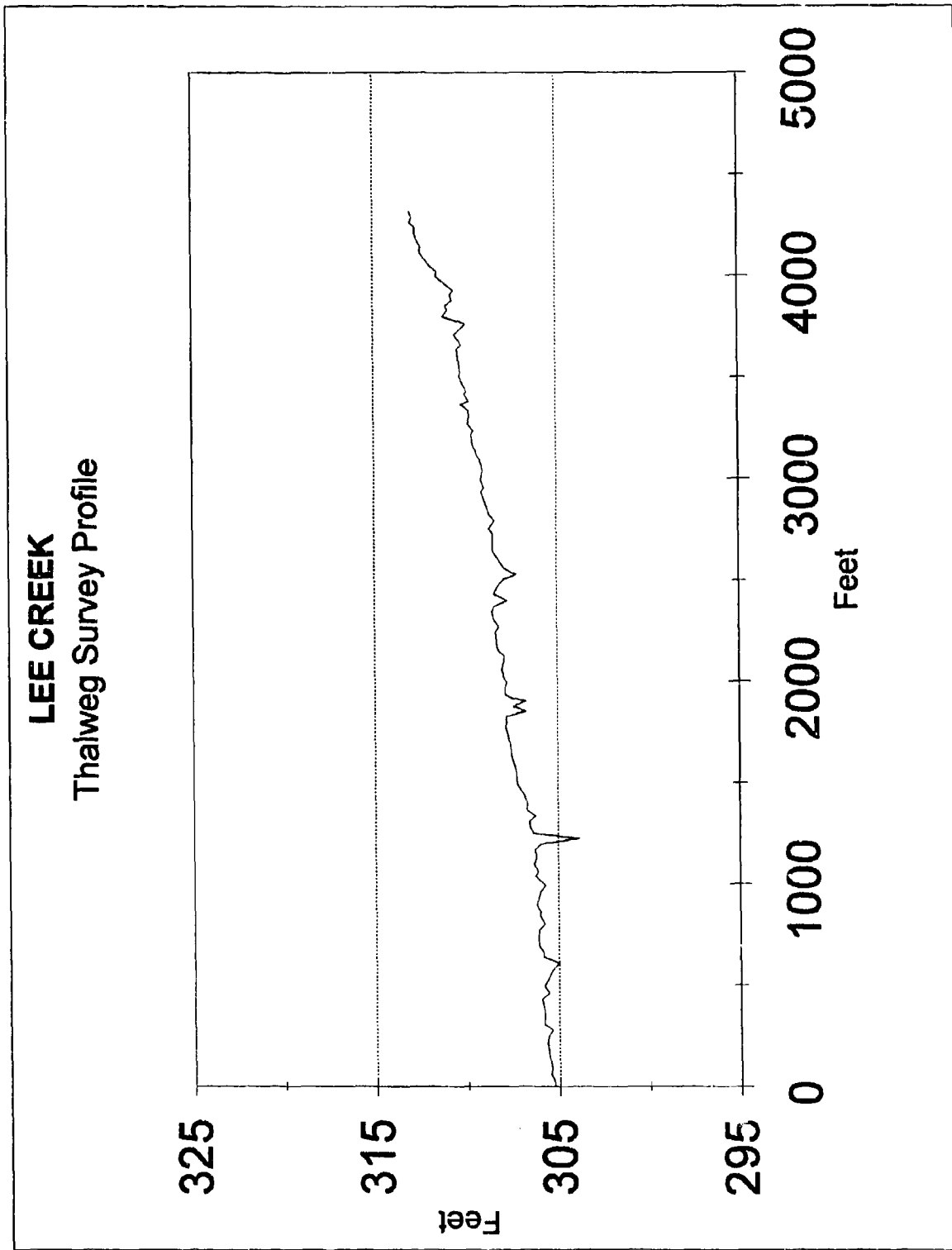


Figure 3.5s Thalweg Profile of Lee Creek for summer 1994 data.

HICKAHALA CREEK Thalweg Survey Profile

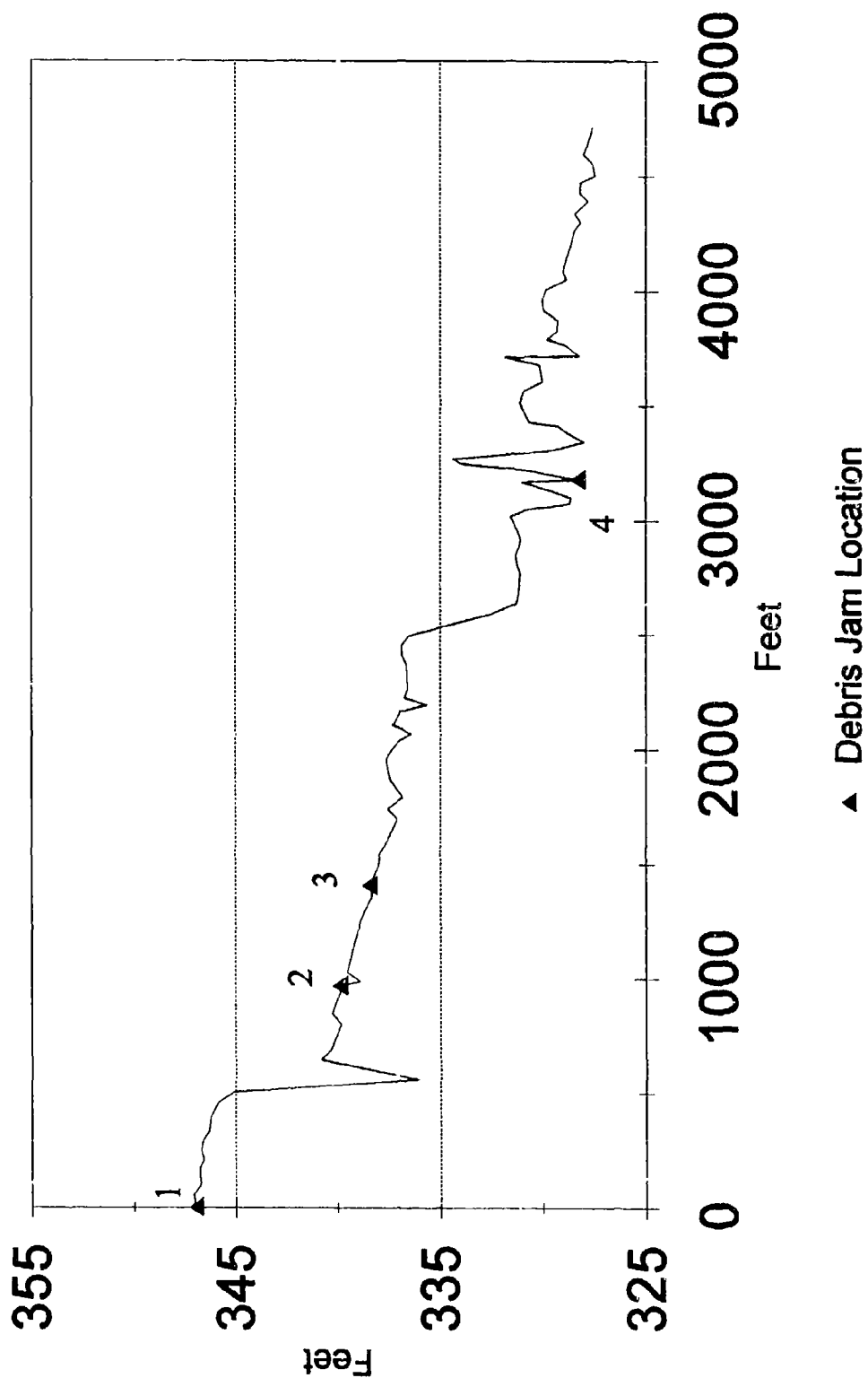


Figure 3.5t Planform of Hickahala Creek for summer 1994 data.

PERRY CREEK Thalweg Survey Profile

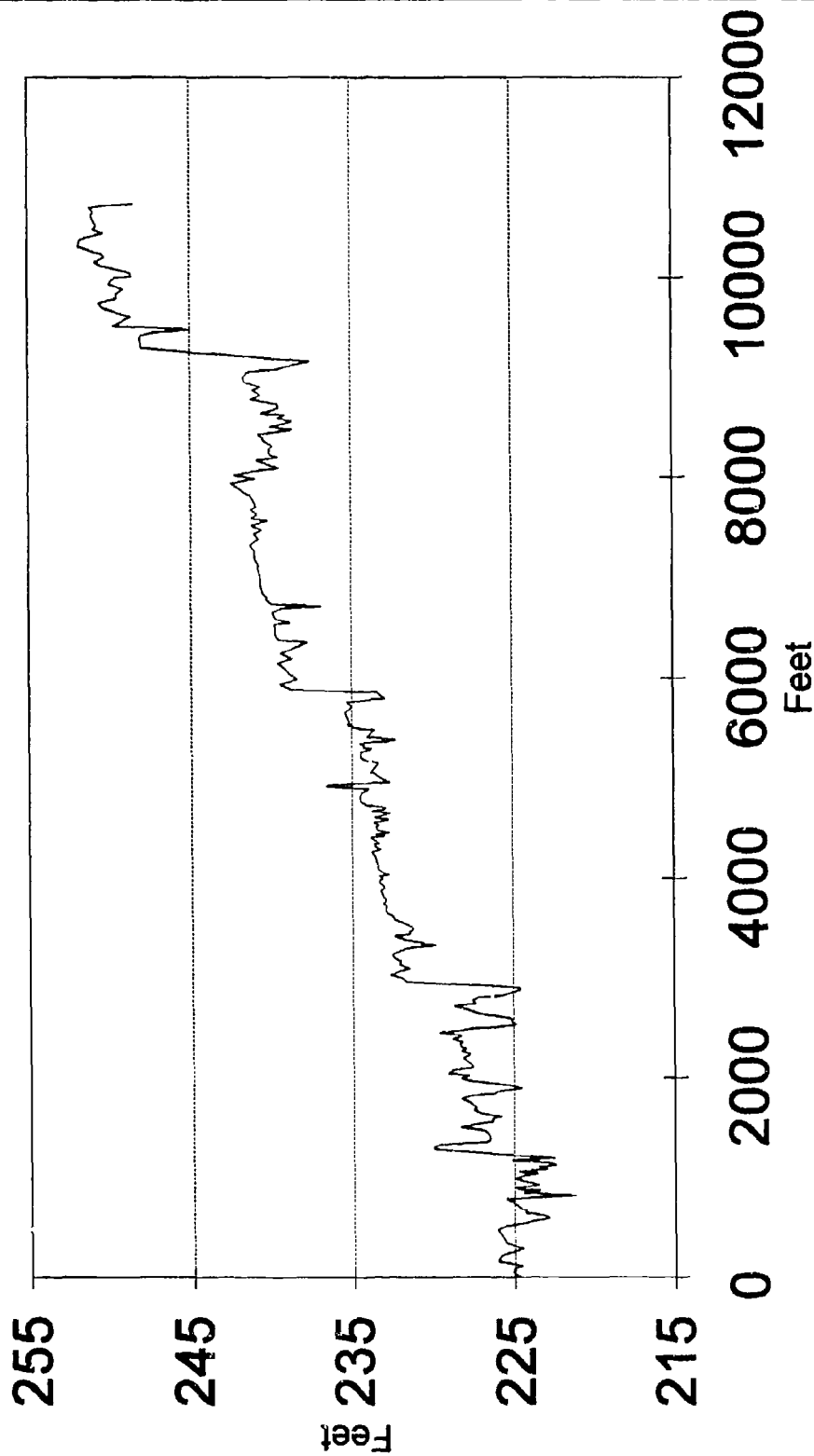


Figure 3.5u Thalweg Profile of Perry Creek for summer 1994 data.

HARLAND CREEK (SITE 23)
Thalweg Survey Profile

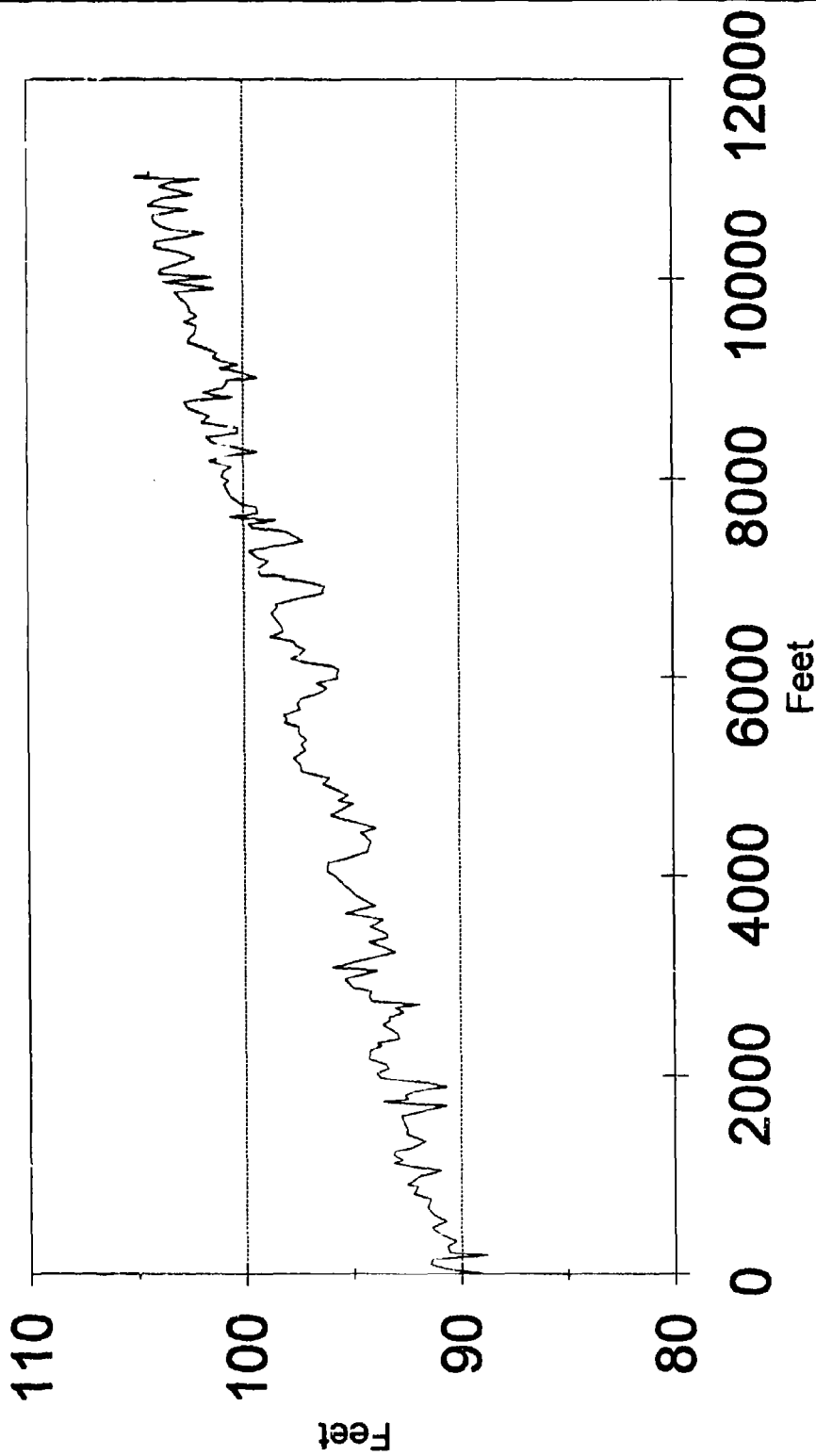


Figure 3.5v Thalweg Profile of Harland Creek, Site No. 23 for summer 1994 data.

4 CONCLUSIONS

4.1 Literature review

The geomorphological impact of woody debris has been extensively studied and documented, however, there remain few in any geomorphological studies in unstable, degrading channel environments. A limited number of studies on the hydraulic effect of LWD have been carried out. A practical method for calculating the Darcy-Weisbach "f" and also the afflux associated with debris accumulations is presented in this report along with a method for calculating pier scour with floating debris accumulations.

4.2 Survey Results

A number of conclusions can be drawn from the initial field survey and data analysis. Firstly, given the entrenched nature of many of the creeks being surveyed, and the permeability of the jams observed, it is unlikely that even the most complete debris dams will cause a serious increase in the level or duration of the over-bank flood potential. Very large, coherent, debris accumulations may occur however at man-made structures, such as against bridge piers, and without periodic clearance these will eventually cause a greater local flood risk.

It is worth considering the fact that large, coherent debris accumulations, such as that show in plate 3, will significantly affect channel hydraulics, through backwater effects, so obstructions such as this must be considered when mathematical flow routing models such as HEC 2 are used to calculate channel capacity and energy gradients. Large debris jams could be incorporated as either very high local roughness values or as geometric elements in the channel profile.

From field observations it is apparent that the main LWD input mechanism in these channels is tree topple due to bank failure. Also in November 1993, over the period of one or two days, a heavy frost caused branches to tear off a large number of trees in the northern half on the DEC survey area causing a sudden influx of new debris material into many catchments. It appears, however that, much of this load, because it is composed of only limbs, rather than whole trees, has been moved by high flows to previously established debris jam, rather than forming new sites of obstruction.

On a catchment-wide scale it is becoming apparent that major debris input regions and jam concentrations are to be found in laterally unstable reaches, especially downstream of knickpoints and knickzones. It is also apparent that the input of debris from the outside of actively migrating meander bends from both stable and unstable channels is significant as a large proportion of the total number of jams surveyed can be found at the apex of bends, while significant debris input in straight channels is limited to those channels which are highly unstable (for example Nolehoe Creek). Meander apexes are also a preferential site for deposition of debris which has been floated from upstream. This is likely to be due to the propelling of debris to the outside of bends by centrifugal force and outward flowing secondary currents at the water surface. During high flow events debris then becomes snagged in vegetation or is pinned to the bank and deposited at its based as high flows recede.

In channels with a catchment area greater than 50 square miles coherent jams appear unable to form as even the "key-debris" (whole mature trees) can be transported at the higher flows without becoming stuck in the channel. It appears therefore that there is a limiting catchment size (channel width) from with larger debris is made available to downstream areas. This has important management implications for controlling debris at "run-of-the-river" structures such as bridges, locks and weirs and dams, because at-source debris management (riparian vegetation management) can be limited to channels above a given size.

Current thalweg profile plots provide little conclusive evidence about the magnitude of debris-jam related scour or sediment retention, but once again, future surveys of each reach will show exactly where and to what extent erosion and/or sedimentation is prevalent in debris filled reaches as compared to those which are debris-free. It is evident from the thalweg plots however that debris filled reaches have far more irregular bed topographies than those which are completely debris-free. It likely that debris filled reaches with their debris induced pools and shallows and abundant nutrient supply from the decomposing woody material will offer a more diverse habitat than debris-free uniform reaches, for aquatic flora and fauna (see Bilby & Likens, 1980).

As yet little information is available concerning the age and stability of particular debris jams, a crucial factor which must be considered for any effective management strategy. A rough estimation of the relative age of in-channel trees can be made through observing the state of decay of the debris in question but this does not necessarily mean that the debris has always resided at that particular location in the channel network since its input. Such time trends will become apparent however as future data from the semi-annual surveys is collected. The working hypotheses and theoretical relationships developed for debris input, residence times and output from the channel network which will be tested using the semi-annual survey information are as follows:

1) Debris Input Distribution

There are two components to debris input to the channel; spatially random and spatially probabilistic.

a) Spatially random : Inputs due to tree death, leaf/litter fall, ice loading, beaver activity and windthrow.

b) Spatially predictable : Inputs due to tree topple through:

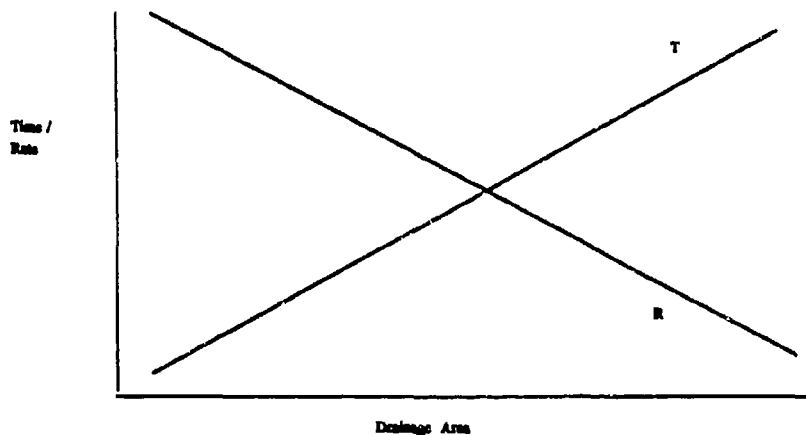
i) Bank erosion in actively meandering stable channels;

ii) Channel instability through degradation which leads to bank failure in oversteepened zones.

2) Debris spatial residence times

As drainage basin area increases, with distance downstream in the fluvial system, so does discharge and average channel width. Woody debris transport rate is, therefore, also likely to increase downstream (see Figure 4.1).

Figure 4.1 Schematic plot of Debris Residence Time versus Basin Area



R = Residence time of debris at any particular location in the channel network.

T = Transport rate of debris through the network

These trends also reflect the operation of debris jams in a particular reach. The total volume of debris present in a channel reach may well increase downstream, but is more mobile and is routed out of the system during high flows. Owing to the larger size of downstream channels and greater mobility of debris, coherent jams are unable to form.

The rate at which debris moves through a particular reach will increase as flow competence increases. Transport capacity will also increase.

Residence time and transport rate will also determine the extent to which particular debris jams are effective in modifying the morphology and stability of the channel reach in which they are located.

3) Debris Output Rates

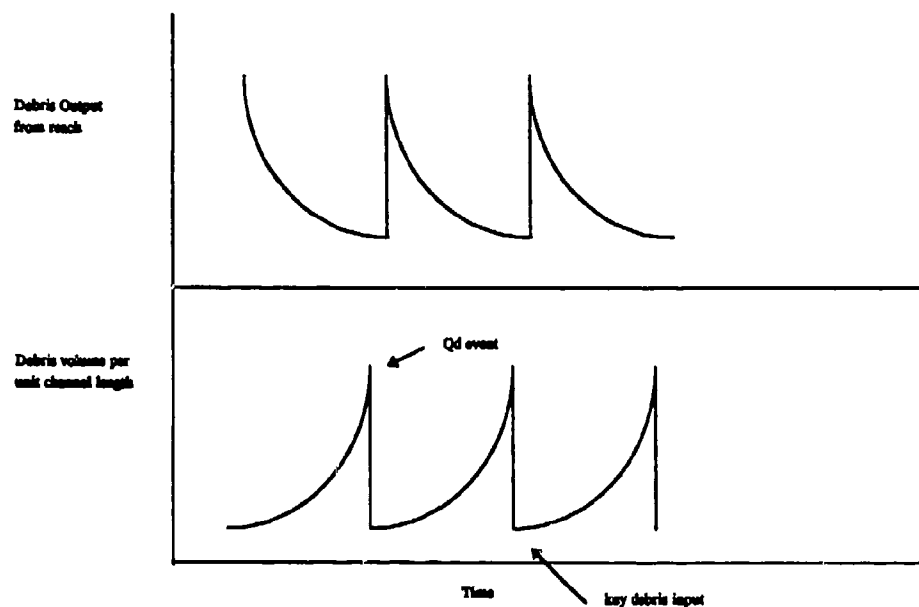
The rate of debris output from upland streams is an important variable for debris management in larger waterways where debris may be a problem at locks, dams, bridges and weirs. Output of debris from a catchment will depend upon the occurrence of flows capable of removing upstream debris jam obstructions and transporting debris into the navigation reach. Low flows are likely to transport smaller debris material which may be trapped by more coherent debris jams so that the jams are built up over time. High in-bank flows will, in larger catchments, have the power to remove coherent jams and flush a large amount of debris out of the headwater system into the downstream reaches. High flows will also cause bank erosion, and trigger bank mass failure particularly during and after the flow has receded (due to bank saturation) which will cause the input of another set of "Key-debris" against which new jams can form. Receding overbank flows will also transport woody debris to the main channel if the flow returns through wooded floodplain, however, large potential "Key-debris" is less likely to be floated into the channel network because it has a greater probability of being "strained out" by the standing floodplain vegetation.

It is important to note that debris volume build-up is not linear because jams become more structured and less permeable over time so that their trapping efficiency increases. Conversely, debris output from a reach will decrease over time until the next jam breaking flood event occurs (see Figure 4.2).

It is therefore necessary to define a dominant discharge for jam removal (Q_d) and its return period with respect to major debris flushing in order to develop an efficient, cost effective

management strategy. (For example, advising structure inspection for debris build-up with a frequency higher than the expected Qd return period).

Figure 4.2 Time distribution of debris storage and flushing in small upland catchments.



4.3 Debris at Structures

Substantial woody debris accumulations were noted at a number of bridges, grade control structures and bendflow weirs during the survey period. Plate 6 shows a debris accumulation against the piers of a county road bridge over Hickahala Creek (11), Site 1. There does not appear to be any significant basal scouring associated with this jam, but the increased pressure force during high flows due to debris loading at each piers may compromise the structural integrity of this bridge. Plate 7 shows a debris accumulation against the baffle of a grade control structure on Hickahala Creek (11). This accumulation is as yet not large enough to cause a significant reduction in capacity in the stilling basin, or cause a backwater effect above the weir jump level. Plate 8 shows two bendway weirs on Harland

Creek (23) which are designed to induce bank-base sedimentation on the outside of eroding bends. Woody debris has been brought to rest on, or between, many of these weirs and incorporated into the accumulating sediment wedge. Larger debris, however, also appears to cause the displacement of riprap from these structures during high flow.

4.4 Drainage Basin Debris Management Program

A Debris management program, written in C++, has been coded and tested. Input data takes the form of those variables that have been found, through the current research, to be significant in terms of jam-channel interaction. The program outputs geomorphic management support information, describing the type and impact of debris jam likely to be present (see Wallerstein & Thorne 1994) and also calculates potential scour and flow afflux at bridge piers due to debris build-up using Melville and Dongol's scour model (see section 2.5). The executable program, source code and user support document is included with this report on a disk. The disk is in a pouch inside the back cover. Appendix E contains a hard copy of the user manual.

The program structure is shown in Figure 4.3. Other variable to be added to this program will include channel stability, channel sinuosity, other in-channel structures and debris input rate and residence time which will provide a vital temporal dimension to the management strategy. A GIS data-input interface for the program is also currently being developed which will feed the necessary data directly into the program when a button representing the channel reach in question, displayed on the screen, is "clicked" on.

4.5 Future Work

Because all major debris jams in the DEC creeks have now been surveyed in, their position and stability can now be monitored through future surveys which will provide vital information for developing a management strategy. Subsequent surveys will also show whether there are any significant changes in bed elevation associated with the presence of debris jams, either basal scour due to potential energy dissipation, or sedimentation due to backwater ponding, and will show how debris jam influence changes with drainage basin area (a surrogate of discharge). In order to obtain a better grasp of debris-channel interactions a "paired catchment" approach will now be employed involving the comparison of degrading

channels in catchments with agricultural riparian land use (i.e. no debris) against degrading channels in catchments with a wooded riparian zone (debris input). Comparisons will also be made between stable and unstable channels with, and without, a heavy debris load. the processes in the stable and degrading channels will then be compared. Suitable catchments for this more focused analysis will be selected from the current data set and intensive thalweg and cross-section surveys carried out at specific jam sites in the forthcoming field visit.

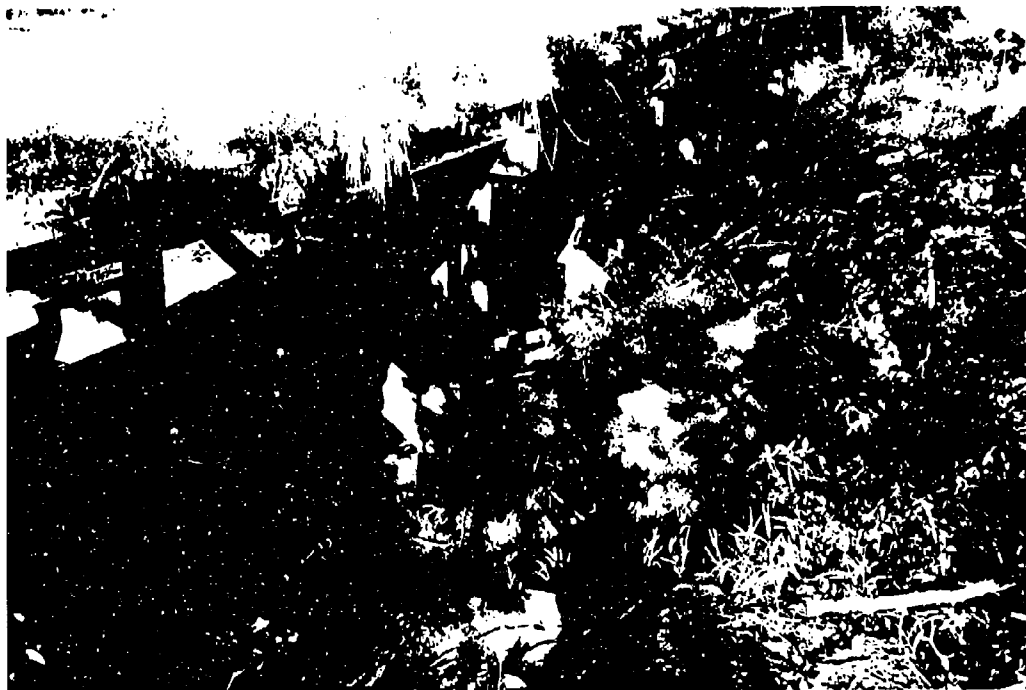


Plate 6 : Debris accumulation against bridge piers. Hickahala Creek (11), Site 1

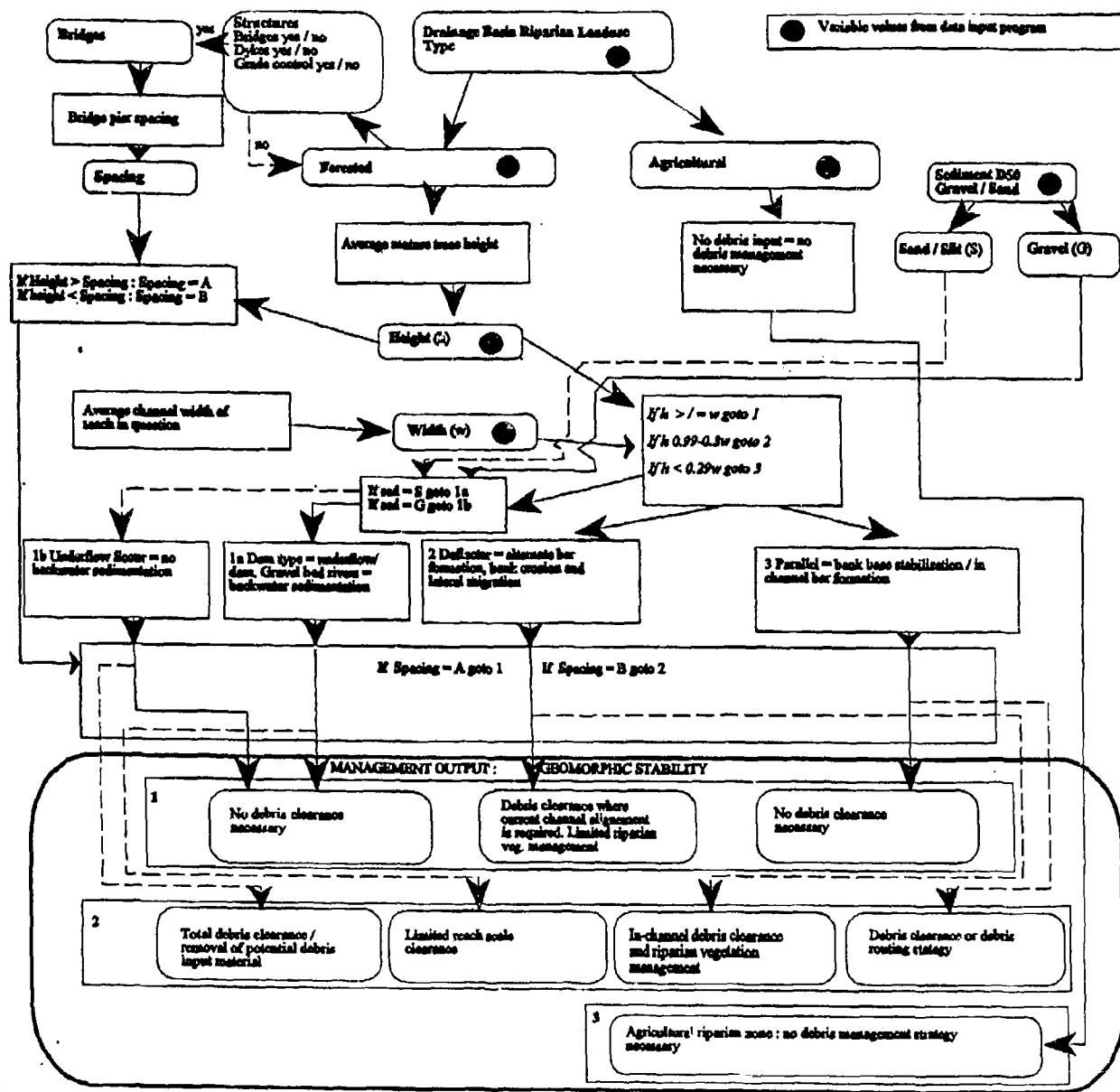


**Plate 7 : Debris accumulation against baffle at grade control structure.
Hickahala Creek**



Plate 8 : Whole tree and smaller timbers on bendway weirs. Harland Creek (23)

DEBRIS MANAGEMENT SUPPORT SYSTEM: DATA PROCESSING PROGRAM Figure 4.3



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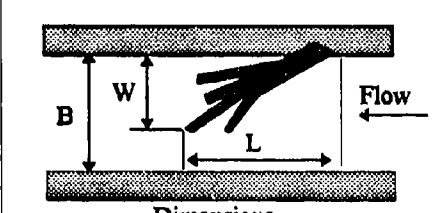


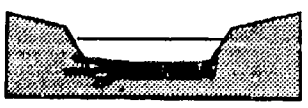
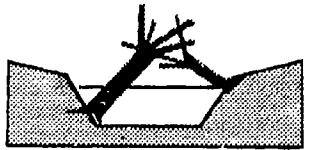
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Table 3

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APPENDIX B

Large Woody Debris Formation Survey used by Smith And Shields (1992)

| <p>Stream Name _____</p> <p>Reach Information _____</p> <p>_____</p> <p>_____</p> <p>Date _____ Time _____</p> |  <p style="text-align: center;">Dimensions</p> | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|--|-----------------|-----------------|---------------|-----------|--|--|--|---------------|--|--|--|---------|--|--|--|---|--|-----------|-----------------|---------------|--|--|--|--|--|--|--|--|--|--|--|--|
| <p style="text-align: center;">Width-Perpendicular to Flow Direction</p> <table border="1" style="width: 100%; text-align: center; border-collapse: collapse;"> <tr> <th></th> <th>$W < B/4$</th> <th>$B/4 < W < B/2$</th> <th>$B/2 < W < B$</th> </tr> <tr> <th>$L < B/2$</th> <td></td> <td></td> <td></td> </tr> <tr> <th>$B/2 < L < B$</th> <td></td> <td></td> <td></td> </tr> <tr> <th>$L > B$</th> <td></td> <td></td> <td></td> </tr> </table> <p style="text-align: center;">Length-Parallel to Flow Direction</p>  <p style="text-align: center;">TYPE A : COLLAPSED BRIDGE</p> | | $W < B/4$ | $B/4 < W < B/2$ | $B/2 < W < B$ | $L < B/2$ | | | | $B/2 < L < B$ | | | | $L > B$ | | | | <p style="text-align: center;">Width-Perpendicular to Flow Direction</p> <table border="1" style="width: 100%; text-align: center; border-collapse: collapse;"> <tr> <th></th> <th>$W < B/4$</th> <th>$B/4 < W < B/2$</th> <th>$B/2 < W < B$</th> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> </table>  <p style="text-align: center;">TYPE B : RAMP</p> | | $W < B/4$ | $B/4 < W < B/2$ | $B/2 < W < B$ | | | | | | | | | | | | |
| | $W < B/4$ | $B/4 < W < B/2$ | $B/2 < W < B$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| $L < B/2$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| $B/2 < L < B$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| $L > B$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | $W < B/4$ | $B/4 < W < B/2$ | $B/2 < W < B$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| <table border="1" style="width: 100%; text-align: center; border-collapse: collapse;"> <tr> <th></th> <th></th> <th></th> <th></th> </tr> <tr> <th>$L < B/2$</th> <td></td> <td></td> <td></td> </tr> <tr> <th>$B/2 < L < B$</th> <td></td> <td></td> <td></td> </tr> <tr> <th>$L > B$</th> <td></td> <td></td> <td></td> </tr> </table> <p style="text-align: center;">Length-Parallel to Flow Direction</p>  <p style="text-align: center;">TYPE C : DRIFT</p> | | | | | $L < B/2$ | | | | $B/2 < L < B$ | | | | $L > B$ | | | | <table border="1" style="width: 100%; text-align: center; border-collapse: collapse;"> <tr> <th></th> <th></th> <th></th> <th></th> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> </table>  <p style="text-align: center;">TYPE D : STREAMBANK TREES</p> | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| $L < B/2$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| $B/2 < L < B$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| $L > B$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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APPENDIX C

Method for predicting afflux due to LWD, developed by Gippel et. al. (1992)

The recommended procedure for predicting the hydraulic effect of managing large woody debris from a lowland river is as follows:

- 1) Measure the LWD:
 - projected length of LWD (L_p)
 - mean diameter of LWD in flow (d)
 - angle of orientation of the LWD in the flow (α)
- 2) Measure the channel morphology:
 - cross-sectional area of flow at selected discharge (A)
- 3) Measure or estimate flow characteristics at selected discharge:
 - depth of flow downstream of LWD (h_3)
 - velocity downstream of LWD (U_3)
- 4) Select a drag coefficient:
 - based on angle of orientation and snag form (C_D) using Figure 5.2 or 5.3

Figure 6.1 Variation in drag coefficient with angle of rotation to the flow, measured for a model LWD complete with trunk, branches and butt, and for other combinations of these components

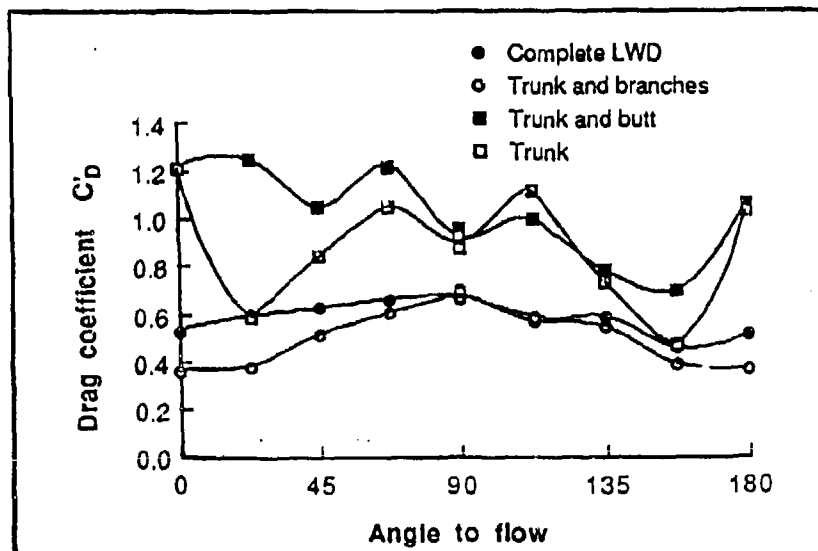
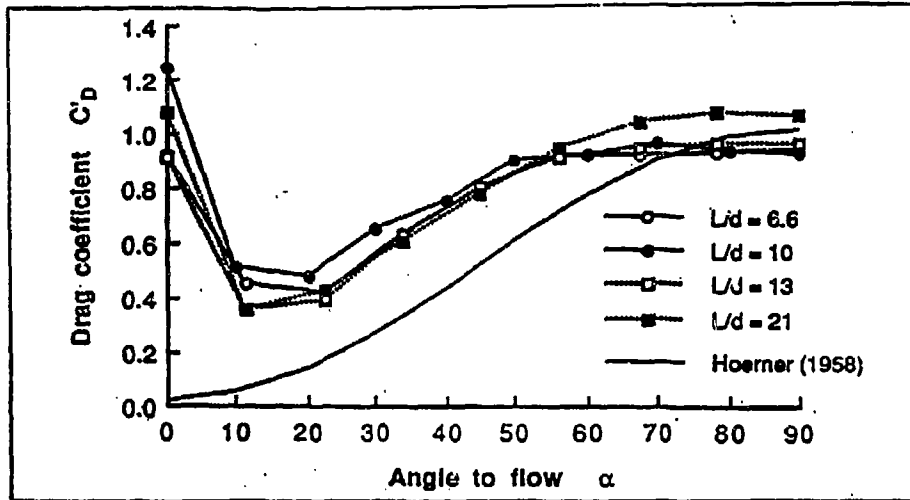


Figure 6.2 Variation in drag coefficient with angle of rotation for cylinders of various lengths and diameters. Hoerner's (1958) relationship is for infinitely long cylinders.



5) Calculate the following:

- Froude number downstream of LWD

$$F = \frac{U_3}{\sqrt{gh_3}}$$

- blockage ratio of LWD

$$B = Lwd / A$$

- drag coefficient corrected for blockage

$$C_D = C'_D(1-B)^{-3}$$

6) Calculate afflux due to LWD:

$$\Delta h = \frac{h_3 \left[(F^2 - 1) + \sqrt{(F^2 - 1)^2 + 3C_D B F^2} \right]}{3}$$

7) Calculate the upstream extent of the afflux using a backwater procedure

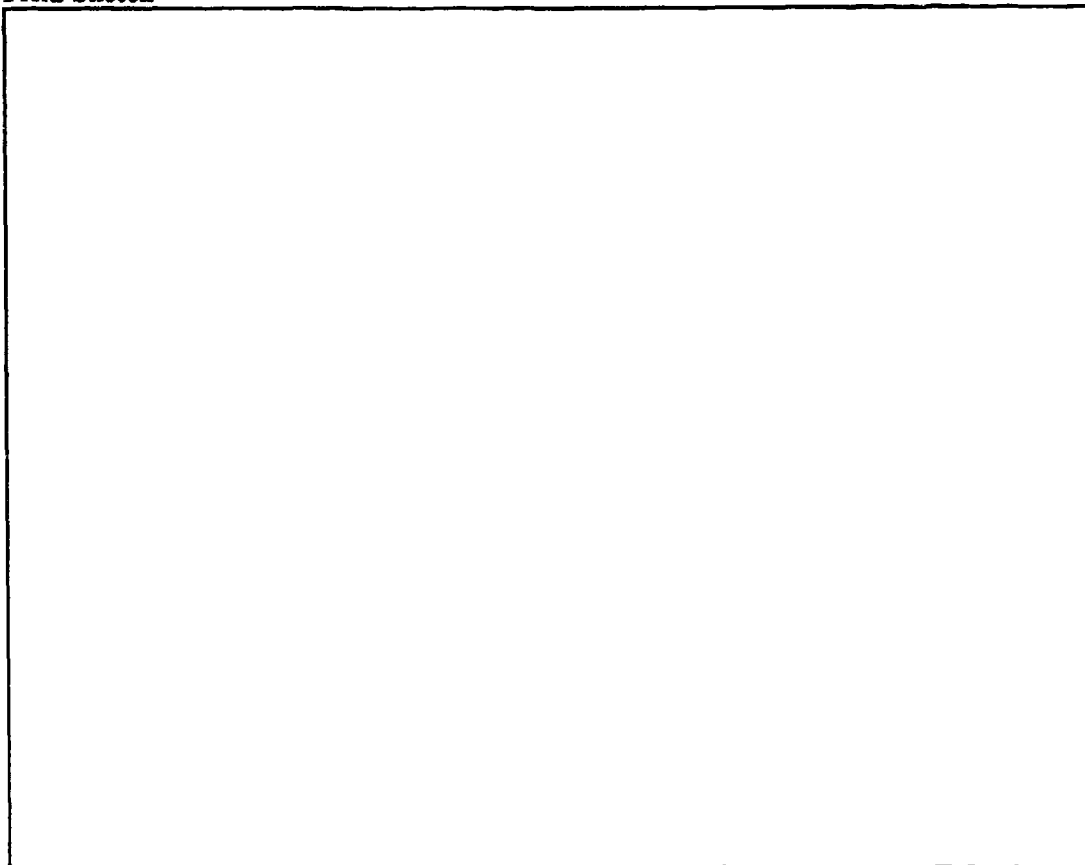
8) Repeat the calculations for various management strategies such as lopping and rotation.

APPENDIX D

DEBRIS JAM FIELD RECONNAISSANCE FORM

Site Location _____ Site No. _____
Map Reference _____ Date _____
Special Features _____ State of Flow _____

Field Sketch



JAM CHARACTERISTICS

| Barrier to flow and sediment routing (1) | | max height of jam | % of channel cross-section blocked by jam (2) | Jam Flow Direction | | zones occupied by jam (3) | % |
|--|--|-------------------------|--|-----------------------|--|------------------------------|---|
| Active | | | | Dam | | 1 | |
| Complete | | | | Deflector | | 2 | |
| Partial | | | | Underflow | | 3 | |
| | | | | Flow Parallel | | 4 | |

Alpha angle of key debris _____ (4)

Beta angle of key debris _____ (5)

Channel Planform _____ Knickpoints/zones _____

| Sedimentation | Location in channel | Estimated area / depth |
|--------------------------|---------------------|------------------------|
| Backwater Sediment Wedge | | |
| Bar | | |

| Erosion | Location in channel | Estimated area / depth |
|--------------|---------------------|------------------------|
| Bed scour | | |
| Bank erosion | | |

| Bank Erosion Severity | 1 | 2 | 3 | 4 |
|-----------------------|---|---|---|---|
| Left | | | | |
| Right | | | | |

| Sediment Type | Gravel | Sand | Silt | Clay |
|---------------|--------|------|------|------|
| Estimate D50 | | | | |

| Vegetation Characteristics | Type / Species | Estimated age | Position on bank/in channel | Estimated height/diameter |
|----------------------------|----------------|---------------|-----------------------------|---------------------------|
| Debris Jam | | | | |
| Riparian | | | | |

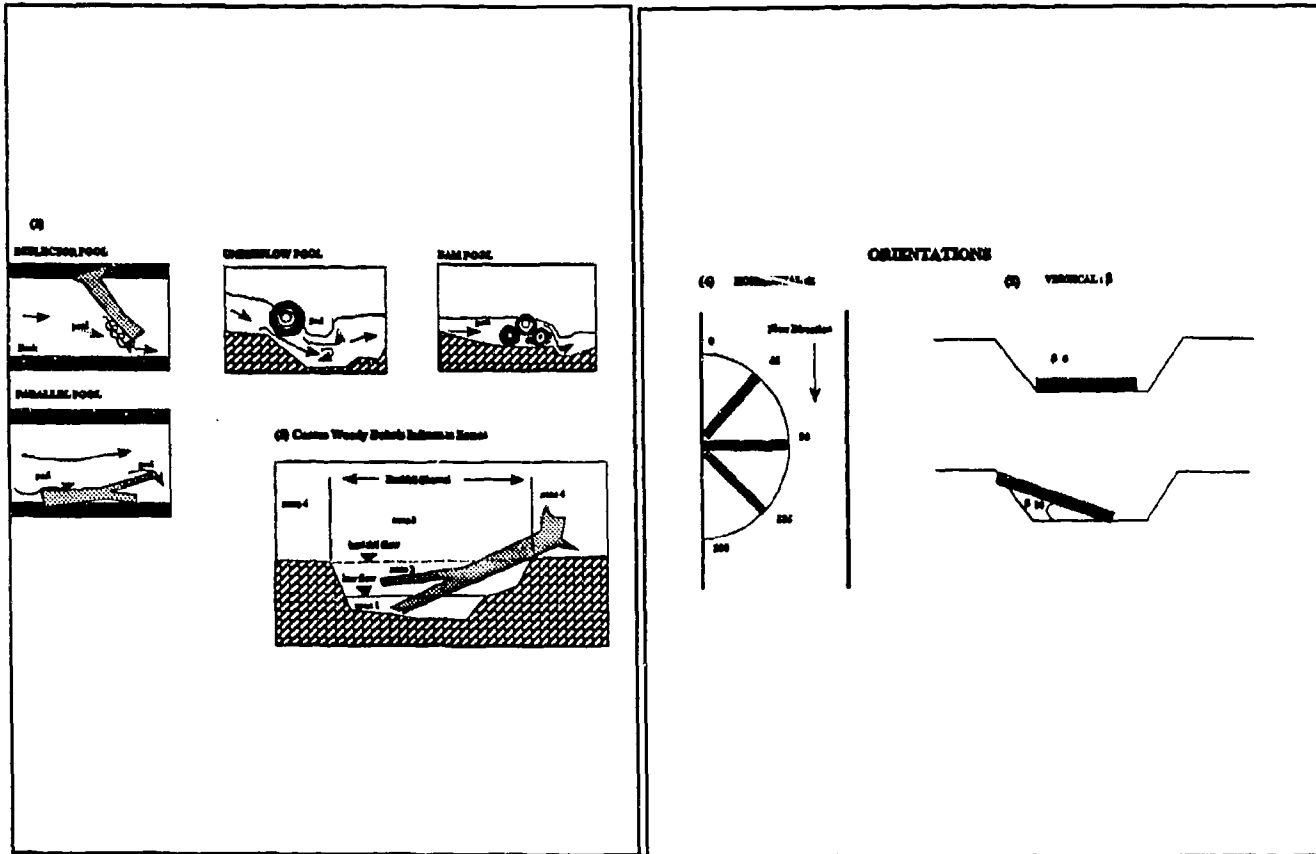
Notes

(1)

Active: jam forms a complete barrier to water and sediment movement and also creates a distinct step, or fall in the channel profile

Complete : complete barrier to water/sediment movement, but no significant step

Partial : jam is only a partial barrier to flow



(6) Bank Erosion Severity

- 1) None : very stable, no evidence of significant erosion
- 2) Slight : small area of bank failure, not continuous or widespread
- 3) Moderate : significant portion of the banks are eroding, however, rate does not appear excessive
- 4) Severe : banks are continuously eroding along the length of the site

APPENDIX E

Debris Management Program Version 1: User Manual

Introduction

This manual describes version 1 of an on-going developmental program designed to aid engineers, geomorphologists and planners with management of woody debris in river channels throughout the catchment network.

The source code for the computer model is written in C++ and is contained on an MS-DOS formatted disk, labelled "DEBRIS" along with an executable version of the code.

The program will run on most IBM compatible PCs. It is recommended that the program should be installed in a directory on the hard drive of the PC. This program may be freely copied, but the source code may not be distributed to other parties. The author accepts no responsibility or liability resulting from the use of the program.

Installation

To install the program onto your hard drive first make a new, appropriately named, directory then copy the file named DEBRIS.EXE from the disk to the new directory.

Background

This program is pilot version of the Debris Management Support System which is currently being developed. In this version of the program the input variables are entered by the user from data collected in the field, and from secondary data sources such as maps. It is intended that in the final version of the system the data will be fed

to the program from a GIS system (Intergraph or ARC/INFO) when the user specifies the channel site of interest on the GIS platform.

Management Output strategies are based upon the relationships between variables which are under investigation in the current research. As a better understanding of woody debris in the channel network is developed so the program will be amended and updated.

Running the program

It should be noted that the required units for data entry in this program are SI (millimetres, metres, kilometres).

The program is divided into two sub-programs BASIN and BRIDGE.

BASIN gives a debris management support output based upon the geomorphological impact of woody debris.

BRIDGE calculates scour at bridge piers, both due to the pier and the pier plus a debris accumulation and calculates the change in water depth due to debris blockage. It should be noted that the formula for calculating debris related scour was intended for only floating debris accumulations, however the method is also applicable to debris accumulation which rest on the channel bed.

Run the program by typing "**debris**" from the appropriate directory.

The initial menu asks you to select "**BASIN**" or "**BRIDGE**" or press "**q**" to quit the program. (Note, in this program character input is not case sensitive, **Q** or **q**, **BASIN** or **basin** can be entered.)

BASIN

- 1) Select BASIN by typing "**basin**".
- 2) Enter a **file name** for the output text file e.g. "**basin1.txt**"
- 3) Enter the riparian vegetation type that is predominantly found along the reach of river in question. A simple distinction is made between forested and agricultural. Enter "**forest**" or "**agricultural**".

If "**agricultural**" is entered the next prompt will ask if you wish to run the program again. Type "**y**" or "**n**".

- 4) If "**forest**" is entered the next prompt will ask you to enter the **average riparian tree height** (metres)
- 5) Enter the **drainage basin area** (kilometres square) of the reach in question. This parameter is used to calculate an average channel width based upon a selected width function.
- 6) **Average channel width** can either be calculated using the default formula which is appropriate for channels in northern Mississippi, or the user can enter their own formula. The default formula is :

$$\text{average channel width} = 46.77 \times \text{Da}^{0.24}$$

where Da = drainage basin area in square miles. This is converted to square kilometres by the program. This formula is taken from the empirical relationship developed by Schumm, Harvey and Watson (1984).

Select "**n**" to use the default function or select "**y**" to enter a new function.

A new function takes the form of :

$$\text{average channel width} = \text{constant (a)} \times \text{drainage area}^{\text{constant (b)}}$$

The user is prompted first for **constant a**, then for **constant b** both of which must be numerical values from functions developed in SI units. Note constant b must be less than 1 else the program will crash.

The program will then output the average channel width to the screen.

7) Enter the channel bed sediment type. A simple distinction is made between sand and gravel. Type "**sand**" if the mean bed grain size is less than 2 mm. Type "**gravel**" if the mean bed grain size is greater than 2 mm.

8) Enter whether or not there is a bridge present in the study reach. Type "**y**" if there is a bridge present, else type "**n**".

If "**y**" is selected the user is prompted to enter the **bridge pier spacing** (metres). This means the *minimum* horizontal distance between bridge piers at 90 degrees to the direction of flow.

9) The user will then be asked whether they wish to run the program BASIN again. Enter "**y**" or "**n**". If "**y**" is typed the program will run again and return to the prompt asking for the riparian vegetation type. If "**n**" is typed a prompt will ask whether the user wishes to return to the main menu. Again if "**y**" is entered the main program selection menu will return. If "**n**" is selected the program will terminate and return to the operating system.

BRIDGE

1) Select **BRIDGE** from the main menu by typing "**BRIDGE**".

2) Enter a **file name** for the output text file e.g. "**bridge1.txt**"

3) A diagram of a bridge pier with debris raft is displayed showing the various parameters that must be entered into the program. The method used for calculating

bridge pier scour in this program is taken from the theoretical and flume based model developed by Melville and Sutherland (1988) and Melville and Dongol (1992) See section 2.5.

The user is prompted to enter the bridge pier diameter "D" (metres).

4) Enter the approach flow depth "Y" (metres).

5) Enter the debris raft length parallel to the flow "Dd" (metres).

6) Enter the debris raft depth "Td" (metres).

7) Enter the debris raft width perpendicular to the flow direction "Dw" (metres).

8) Enter the channel width. If BRIDGE has been run before BASIN the user will be asked if they wish to use the width value calculated in the *last* run of BRIDGE before BASIN was entered. To use the last width value type "y" else type "n" and enter a new width value "w" (metres).

9) The user will asked if they wish to run the program again. Type "y" or "n".

If "n" is entered the user will then be asked if they wish to return to the main menu.

Type "y" or "n". If "n" is typed the program will end and return to the operating system.

Program Output

The results from BASIN and BRIDGE are written to output files. which have the file names specified by the user during each program run. Both of these output files are created in the same directory as the debris.exe file. If either program is unable to create the output file an error message will appear reading "Error opening file". If this happens the program should be terminated.

The output text files can be viewed, once the program has been ended, in any text editor such as MS DOS EDIT or in a word processor such as MS WORD or Word

Perfect. The output files can then be printed out if the machine is connected to a printer device.

Note : If a windows based word processor is used for output display the files should be converted from the default font to courier 10 pitch font type.

Successive outputs from each program will be added sequentially to the same text files if the file names are not altered by the user during each run. Successive program runs are distinguished by a numbered header. (e.g. program run number 1..... program run number 2..... etc.).

Output from BASIN

Management Outputs take a standard format.

- 1) A "Debris Management Output" header.
- 2) The input parameters are displayed
- 3) A description of the debris-channel interaction. Potential debris jam types are classified by the forms described in Wallerstein (1994) as **Underflow, Dam, Deflector** and **Flow Parallel** types. The type of jam present will determine the geomorphological impact of the debris jams in terms of potential bank erosion and bed scour. The output will give a brief description of the potential impact.

A management recommendation based upon the geomorphological impact is displayed in capital letters.

- 4) If there is a bridge present in the study reach the program will give an output indicating the likelihood of debris jam build-up at the bridge piers. If build-up is likely it is recommended that a site inspection is made and hypothetical or empirical jam dimensions and flow depths run through **BRIDGE** to determine whether the bridge stability might be compromised by debris related pier scour.

Output from BRIDGE

- 1) The input parameters are displayed.
- 2) Then following parameters are displayed in order :

Maximum bed scour at the bridge pier, due to the pier alone (metres).

Maximum bed scour due to the pier and the debris accumulation (metres).

Increase in approach water depth due to flow constriction (metres).

The new total approach water depth (metres).

The schematic diagram of the input parameters.

Test Cases

These examples are provided to ensure that the user is familiar with the procedures used to run the programs, and to check that the supplied program is working accurately.

1. Start the program by typing "**debris**". Select "**basin**".
- 2) Enter an output file name e.g. "basin1.txt"
- 3) Enter the following values :

| | run 1 | run 2 | run 3 | run 4 |
|------------------------------|--------|--------|--------|--------------|
| riparian vegetation | forest | forest | forest | agricultural |
| average tree height | 10 | 10 | 10 | - |
| drainage basin area | 40 | 200 | 20 | - |
| alternative width function ? | n | n | y | - |
| constant a | - | - | 10 | - |
| constant b | - | - | 0.30 | - |
| sediment type | sand | sand | gravel | - |
| bridge present? | n | y | y | - |
| bridge pier spacing | - | 9 | 15 | - |

- 4) Return to the main menu and select "**bridge**".
- 5) Enter an output file name e.g. "bridge1.txt"

6) Enter the following values :

| | run 1 | run 2 | run 3 | run 4 |
|--------------------------------|-------|-------|-------|-------|
| D | 0.5 | 1 | 2 | 1 |
| Y | 3 | 3 | 5 | 4 |
| Dd | 3 | 5 | 2 | 5 |
| Td | 0.5 | 2 | 0.5 | 1 |
| dw | 4 | 5 | 2 | 3 |
| Enter width from basin? | n | n | n | y |
| w | 20 | 10 | 40 | 24.56 |

7) Leave the program and run a text editor or word processor to view the named output files.

8) The output for runs 1 to 4 from BASIN should be as follows:

Program Run Number 1

Debris Management Output

Vegetation type selected is forest
Average riparian tree height 10 metres
Drainage basin area 40 kilometres square
Average channel width is 27.52 metres
Sediment type is sand

Average debris length lies between 0.9 and 0.3 times channel width.
Deflector type jams are therefore likely to be present.
Geomorphological impact is erosion of one or both banks due to flow deflection.
Where width to tree height ratio approaches 1 Dam type jams will form.
Local bed scour is likely under the debris accumulation because the main sediment type is sand. Backwater sediment wedges are less likely to form.
Enhanced bed scour will be undesirable at bridge piers, but also provides a more varied channel topography than that found where no debris is present, which offers better habitat for flora and fauna.
DEBRIS CLEARANCE NECESSARY WHERE LOCALISED BANK EROSION AND BED SCOUR IS UNDESIRABLE.
DEBRIS SHOULD BE LEFT IN PLACE IF HABITAT ENHANCEMENT IS DESIRABLE.

Program Run Number 2

Debris Management Output

Vegetation type selected is forest
Average riparian tree height 10 metres
Drainage basin area 200 kilometres square
Average channel width is 40.49 metres
Sediment type is sand

Average debris length is less than 0.3 times the channel width.
Debris jam type is therefore likely to be Flow Parallel.
Geomorphological impact of this type of jam is minimal, bank erosion and bed scour is unlikely.
Bank toes may be stabilised by debris material, debris may form the core of mid-channel and lateral bars.
DEBRIS CLEARANCE UNNECESSARY.

Bridge present in the study reach.
Pier spacing is 9 metres

Pier spacing is less than the average debris length. Debris jam build-up is likely
Bridge inspection is advisable. Run the program BRIDGE to calculate potential pier scour and flow afflux

Program Run Number 3

Debris Management Output

Vegetation type selected is forest
Average riparian tree height 10 metres
Drainage basin area 20 kilometres square
Average channel width is 24.56 metres
Sediment type is gravel

Average debris length lies between 0.9 and 0.3 times channel width.
Deflector type jams are therefore likely to be present.
Geomorphological impact is erosion of one or both banks due to flow deflection.
Where width to tree height ratio approaches 1 Dam type jams will form.
Because the main channel sediment type is gravel, jam induced bed scour will be negligible.
Backwater sediment wedges and bars may form, both upstream and downstream of the jams.
This process will reduce the rate of sediment routing downstream and help to reduce bank destabilisation through over-deepening in degrading reaches.
DEBRIS CLEARANCE UNNECESSARY, EXCEPT WHERE LOCALISED BANK EROSION IS UNDESIRABLE.

Bridge present in the study reach.
Pier spacing is 15 metres

Pier spacing is greater than the average debris length. Debris-jam build-up is therefore unlikely.

Program Run Number 4

Debris Management Output

Because the immediate riparian zone contains no potential key coarse woody debris substantial jams are unlikely to build up.
Smaller debris may be input from upstream reaches however and debris build-up at structures should be monitored.
DEBRIS JAMS NOT PRESENT.
IF CHANNEL BED IS UNSTABLE AND HAS A SAND SEDIMENT LOAD CONSIDERATION SHOULD BE GIVEN TO ARTIFICIAL DEBRIS INPUT TO IMPROVE AQUATIC HABITAT AND ENHANCE CHANNEL STABILISATION.

9) The output value for runs 1 to 4 of BRIDGE should be as follows :

Program Run Number 1

Maximum Bridge Pier Scour

Pier diameter : D 0.5 metres
Approach flow depth : Y 3 metres
Debris raft length parallel to flow : Dd 3 metres
Debris raft depth : Td 0.5 metres
Debris raft width perpendicular to flow : dw 4 metres
channel width : w 20 metres

Calculations from empirical relationship developed by Melville and Sutherland and Melville and Dongol.

Bed Scour Due to pier (ds) = 1.2 metres

Bed scour due to pier and debris accumulation (dsd) = 1.72 metres

Increase in approach water depth at the bridge (Yd) = 0.07 metres

New total approach water depth (Y+Yd) = 3.07 metres

Program Run Number 2

Maximum Bridge Pier Scour

Pier diameter : D 1 metres
Approach flow depth : Y 3 metres
Debris raft length parallel to flow : Dd 5 metres
Debris raft depth : Td 2 metres
Debris raft width perpendicular to flow : dw 5 metres
channel width : w 10 metres

Calculations from empirical relationship developed by Melville and Sutherland and Melville and Dongol.

Bed Scour Due to pier (ds) = 2.4 metres

Bed scour due to pier and debris accumulation (dsd) = 5.73 metres

Increase in approach water depth at the bridge (Yd) = 0.32 metres

New total approach water depth (Y+Yd) = 3.32 metres

Program Run Number 3

Maximum Bridge Pier Scour

Pier diameter : D 2 metres
Approach flow depth : Y 5 metres
Debris raft length parallel to flow : Dd 2 metres
Debris raft depth : Td 0.5 metres
Debris raft width perpendicular to flow : dw 2 metres
channel width : w 40 metres

Calculations from empirical relationship developed by Melville and Sutherland and Melville and Dongol.

Bed Scour Due to pier (ds) = 4.73 metres

Bed scour due to pier and debris accumulation (dsd) = 4.73 metres

Increase in approach water depth at the bridge (Y_d) = 0.03 metres

New total approach water depth ($Y+Y_d$) = 5.03 metres

Program Run Number 4

Maximum Bridge Pier Scour

Pier diameter : D 1 metres

Approach flow depth : Y 4 metres

Debris raft length parallel to flow : D_d 5 metres

Debris raft depth : T_d 1 metres

Debris raft width perpendicular to flow : d_w 3 metres

channel width : w 24.56 metres

Calculations from empirical relationship developed by Melville and Sutherland and Melville and Dongol.

Bed Scour Due to pier (d_s) = 2.4 metres

Bed scour due to pier and debris accumulation (d_{sd}) = 3.65 metres

Increase in approach water depth at the bridge (Y_d) = 0.07 metres

New total approach water depth ($Y+Y_d$) = 4.07 metres